SUPERCRITICAL FLOW IN CURVED CHANNELS

Hydraulic Model Investigation

Report No. I-109

March 1972

U. S. Army Engineer District, Los Angeles
CORPS OF ENGINEERS
Los Angeles, California

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13. ABSTRACT

The hydraulic experiments on superelevation in curved trapezoidal channels with supercritical velocities were made to verify theoretical computations and model measurements for superelevation in curved channels. This report presents some of the problems encountered in the study and includes the magnitudes of superelevation and flow disturbances and the development of safe design criteria. The objective was to find design criteria that would minimize superelevation, surface waves, and flow oscillations around curves. In the basic study, a trapezoidal channel with a 2.5-ft-wide (model) invert and 1-on-2.25 side slopes was used. Supercritical flow conditions existed for all measurements. Appendix A describes limited superelevation tests of curved channels of circular cross section. Appendix B summarizes model test results of the trapezoidal sinuous channel of Verdugo Wash. The basic study shows that the minimum length of spiral transition should be $1.82\ (VT/\sqrt{gd})$. The average flow superelevation above normal depth was found to be about $0.9\ (V^2T/gR)$ without spirals and $0.8\ (V^2T/gR)$ with spirals.

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FOREWORD

The hydraulic studies reported herein were conducted in the Hydraulic Laboratory of the U. S. Army Engineer District, Los Angeles. Preparation and publication of the report were authorized by the Office, Chief of Engineers, in a letter dated 21 August 1969 to the Director, U. S. Army Engineer Waterways Experiment Station, subject: "Engineering Studies Program," and were accomplished under ES 804, "Department of Hydraulic Design Criteria and Comprehensive Design Procedures."

This report was prepared by Mr. D. A. Barela, Hydraulics Section, Los Angeles District, under the supervision of Mr. A. Robles, Jr., Chief of the Hydraulics Section. LTC H. McK. Roper, Jr., was District Engineer during publication of the report.

The report was reviewed and published by the Waterways Experiment Station. COL Ernest D. Peixotto was Director of the Waterways Experiment Station during publication of the report; Mr. F. R. Brown was Technical Director.

CONTENTS

CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows:

Multiply	By	To Obtain
feet	0.3048	meters
feet per second	0.3048	meters per second
cubic feet per second	0.02831685	cubic meters per second
gallons (U. S.)	3.78543 3.78533	cubic decimeters liters

SUMMARY

The hydraulic experiments on superelevation in curved trapezoidal channels with supercritical velocities were made to verify theoretical computations and model measurements for superelevation in curved channels. This report presents some of the problems encountered in the study and includes the magnitudes of superelevation and flow disturbances and the development of safe design criteria. The objective was to find design criteria that would minimize superelevation, surface waves, and flow oscillations around curves.

In the basic study, a trapezoidal channel with a 2.5-ft-wide (model) invert and 1-on-2.25 side slopes was used. Supercritical flow conditions existed for all measurements. Appendix A describes limited superelevation tests of curved channels of circular cross section. Appendix B summarizes model tests results of the trapezoidal sinuous channel of Verdugo Wash.

The basic study shows that the minimum length of spiral transition should be $1.82 \frac{VT}{\sqrt{gd}}$. The average flow superelevation above normal depth was found to be about $0.9 \frac{V^2T}{gR}$ without spirals and $0.8 \frac{V^2T}{gR}$ with spirals.

SUPERCRITICAL FLOW IN CURVED CHANNELS

Hydraulic Model Investigation

INTRODUCTION

1. The laboratory study of supercritical flow in trapezoidal, curved channels was made for the purpose of obtaining basic information required to establish design criteria. The plan was to study various design curves, with and without spiral transitions, and to ascertain the amount of superelevated flow produced in the curve by high-velocity flows and the consequent disturbance in the tangent downstream from the curve. Specifically, the factors to be determined were: (a) the length of spiral transition required to reduce the excessive disturbance in the curve and the tangent downstream, (b) the height of the superelevated water surface, (c) the pattern of disturbance, and (d) the development of safe design criteria.

2. Twenty experimental tests are submitted in this report. These tests were made in a model with a scale ratio of 1:25. The model simulated a trapezoidal channel with a 62.5-ft* base width and 1-on-2.25 side slopes. Plans for test channels 1-12 are not illustrated; plans for test channels 13-20 inclusive are shown in plate 1. The changes to the model were limited to: (a) the longitudinal slope of the model, (b) length of radius, and (c) the length of spiral transition. The radius of curvatures in the alinement was 850 ft for 10 tests and 885 ft for the other 10, of which 4 of the tests were made with 325-ft and 2 with 600-ft spiral transition curves. Discharges of 35,000 and 45,000 cfs were considered pertinent to the study program.

3. Table 1 lists all tests in order of testing procedure. A summary of the hydraulic elements, curve data, and computed and test values of the superelevated water surface at the outside and depressed water surface at the inside of the curve and their correlation is presented in the table.

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* A table of factors for converting British units of measurement to metric units is presented on page vii.

THE MODEL

Description

4. The model was constructed to an undistorted scale ratio of 1:25 and reproduced approximately 5000 ft of channel (photograph 1). The channel was constructed entirely of timbers and plywood. The joists, which supported the deck, were attached to stringers by means of adjustable bolts. This facility enabled the slope to be varied as needed.

5. Water used in the model operation was supplied from a recirculating system. A venturi meter installed in the inflow line was used to measure the required flow that was carried into the forebay and thence to the model channel. A control gate was used to obtain the required depth at the upstream end of the approach channel.

Scale Relations

6. The accepted equations of hydraulic similitude based upon the Froudian theory were used to express mathematical relations between the dimensions and hydraulic quantities of the model and prototype. General relations used for the transference of model to prototype equivalent, or vice versa, are presented in the following tabulation:

Dimension	Ratio	Scale Relation
Length	L_r	1:25
Area	$A_r = L_r^2$	1:625
Velocity	$V_r = L_r^{1/2}$	1:5
Discharge	$Q_r = L_r^{5/2}$	1:3125

TESTS WITH SIMPLE CURVE, USING CURVE RADII OF 850 AND 885 FT

7. Fourteen tests simulating prototype discharges of 35,000 and

45,000 cfs were made on simple curve designs. The hydraulic elements for the above tests are tabulated in table 1. The test channel plan for tests 13 and 14 is shown in plate 1. The model was set to a particular slope, and test runs were made with discharges of 35,000 and 45,000 cfs on that slope. For each run, the depth of flow was controlled at the upstream end of model by means of a control gate. Water-surface measurements were taken at various intervals and/or at the crest or trough of the waves. Also, the investigation was planned to include measurements of velocity distribution in the curve and in the upstream and downstream tangents. The variations of superelevation of the water surface as measured in the model along the outside wall with various invert slopes are shown in plates 2-15. The profile of the water surface at the outside wall is a measurement above normal depth and is shown as a solid line. Velocity distribution cross sections of test 14 were selected as typical for all tests on the simple curve and are shown in plate 16. The measured water surfaces along the outside and inside walls throughout the entire reach for test 14 are shown in plate 17. Liberal use of photographs was made to record the operation of some of the tests. Photographs of the flows are presented in photographs 2 and 3.

8. The information obtained from the above-described tests and the observations of flow in the model have demonstrated that when supercritical flow enters a direct change from a tangent to a simple curve, the water surface oscillates along the channel, creating zones of maximum and minimum depths on both the inside and outside walls. This oscillating condition also continues into the downstream tangent. From the measured water-surface profiles, all test data were analyzed and tabulated in tables 1 and 2. Tests 1 and 2 apparently produced smooth flow and it appears that the amount of superelevation is low (plates 2 and 3). The crests of the waves for tests 1 and 2 varied in height from 1.7 to 3.4 ft and 1.8 to 4.0 ft above the theoretical normal depth, respectively. The superelevation in the other tests was much higher. The flow in test 14 had the maximum crest height of 10.8 ft above normal depth and maximum height of wave was 17.5 ft from crest to trough (plate 17). The velocity distribution at the entrance to the curve, as shown in plate 16, is symmetrical and uniform. The center and surface velocities are somewhat higher than the normal velocity. The

maximum velocity occurred near the outer wall of the channel in the sections in the curve. The maximum measured velocity was 59.0 fps. A comparison of the simple curve profiles indicates that the invert slope has some effect on the flow entering the curve. For flatter slopes, the wave trough (D.E.) elevations appear to be appreciably below those resulting with the steeper channel slopes. The superelevation in the steeper sloped channel flow is considerably in excess of that for a flatter slope.

9. Tables 1 and 2 present a comparison of the computed and the experimental values. All of the tests made with the simple curve are presented in this table. With the simple curve alone, the average maximum rise in water surface above the normal depth on the outside wall within the curve is about 91.1% of $\frac{V^2T}{gR}$ *, with a range between 76.3 and 108.8%, and only about 68.6% of $\frac{V^2T}{gR - 2SV^2}$ **, with a range between 60.8 and 88.2%. The water surface on the inside wall of the curve depresses about 52.1% of $\frac{V^2T}{gR}$ and about 57.2% of the average rise (91.1% × 57.2% = 52.1%), making a total difference in depth of $(0.911 + 0.521)\frac{V^2T}{gR} = 1.432\frac{V^2T}{gR}$.

10. Referring to table 3 and the data obtained in tests 11-14, the following relations were derived: (a) the maximum average of 3 rises in water surface is nearly equal to the computed $\frac{V^2T}{gR}$ in each test, (b) the total profile average rise ranges from 57.9 to 68.9% of the computed $\frac{V^2T}{gR}$, and (c) the total profile average rise ranges from 57.4 to 63.5% of the maximum average of 3 rises.

* S. M. Woodward and C. J. Posey, Hydraulics of Steady Flow in Open Channels, Wiley, New York, 1941.

** The formula was developed and presented in "Civil Engineering," ASCE - November 1942, by the Los Angeles District Office, from data obtained in the experiments by the California Institute of Technology.

TESTS WITH SPIRALS, USING CURVE RADIUS OF 885 FT

11. The discussion so far has been limited to channel designs with simple curves only. With this design and with supercritical velocities, disturbances in the form of oscillation and excessive superelevation were caused by the sudden change in alinement. The increase in the outside wall height required by the excessive superelevation in the curve and the increase in the outside and inside wall heights downstream required to control the oscillating disturbance emanating from the curve could be eliminated by introducing properly designed spiral transition curves. This part of the report presents the data and results of additional model tests that were conducted to determine the need for and the effectiveness of spiral transition curves located immediately upstream and downstream of the simple curve.

12. A series of tests was conducted upon two lengths of spiral curves, one a 325-ft and the other a 600-ft spiral transition curve. The general procedure in making the tests was the same as that described in paragraph 7 under the simple curve study. To determine the relative merits of the simple curve and simple curve with spirals, both designs were studied under the same discharge conditions. The comprehensive test program, hydraulic elements, and model data, consisting of the six tests with spirals (tests 15-20), are outlined in table 1. Table 3 presents a comparison of values between these data and similar data obtained with the simple curve only, tests 11-14.

13. Plan of test channel with the 325-ft spiral transition curves, tests 15-18, is shown in plate 1. This plan has a curve 2146.54 ft long and a radius of 885 ft. Measurements of the water surface along the outside wall of the curve were plotted for two discharges and two different invert slopes to determine the magnitude of the superelevation due to the upstream spiral. The water-surface profiles obtained for these tests are shown in plates 18-21. The superelevation (the rise above normal at the water surface along the outside wall) was found to be appreciably less for a slope of 0.010 than for higher slopes with the same discharge because the velocities were lower and their distribution was more uniform. The

flow seems to enter and leave the simple curve in a symmetrical pattern and wave ride-up in the downstream tangent is negligible. For a slope of 0.010, the superelevation did not exceed 6.7 ft for 45,000 cfs and 5.5 ft for 35,000 cfs (plates 18 and 19). For a slope of 0.01575, the maximum superelevation was 9.4 ft for 45,000 cfs and 6.2 ft for 35,000 cfs (plates 20 and 21). The measured water surface along the outside and inside walls throughout the entire reach, including the spirals and tangents, and the velocity distributions for test 18, are shown in plates 22 and 23, respectively. The velocity distributions are shown by contours and are viewed looking downstream; the contour interval is not uniform. Flow conditions for this test plan are shown in photographs 4 and 5.

14. The plan of test channel with the 600-ft spiral transition curves, tests 19 and 20, is shown in plate 1. The length of the simple curve was 1868.40 ft with a central angle of 120°57'36". The total deflection angle was 160°00'00". Tests on this design disclosed a greatly improved flow condition over the 325-ft spiral design, which was probably due to the longer spiral curves. The tests showed satisfactory results in which the spirals provided smooth flow throughout the simple curve and uniform depth in the downstream tangent for discharges of 35,000 and 45,000 cfs. No transverse waves were formed in the curve or in the tangent downstream. Throughout most of the reach, the water surfaces for the two discharges were lower on the 600-ft spiral design than on the 325-ft spiral design for the same discharges. The water-surface profiles are shown in plates 24 and 25, and the water-surface profiles along the outside and inside walls for the entire reach for only the 45,000-cfs discharge (test 20) are shown in plate 26. The differentials in water depth between the outside and inside wall profiles were greatly reduced. The maximum superelevation was 7.6 ft for a 45,000-cfs discharge and 7.0 ft for a 35,000-cfs discharge. When the water-surface profiles for tests 19 and 20 are compared, little difference occurs in the configuration; however, this is not so when the water-surface profiles for tests 17 and 18 are compared. The main deviations between the two profiles were at points in the curved channel where large waves existed. The velocity distributions for a discharge of 45,000 cfs are shown in plate 27. The measured velocities were no

greater than those in the 325-ft spiral design. Photographs 6 and 7 show the performance of the test channel for discharges of 35,000 and 45,000 cfs. Flow conditions were very good.

15. With spirals, the average maximum rise in water surface above normal depth on the outside wall within the curve is about 83.3% of $\frac{V^2T}{gR}$ with a range between 74.7 and 97.1% and only 53.4% of $\frac{V^2T}{gR - 2SV^2}$ with a range between 46.9 and 59.1% (table 1). The average depression of the six tests is about 51.2% of $\frac{V^2T}{gR}$ and about 61.5% of the average rise (83.3% × 61.5% = 51.2%), giving a total difference in depth of $(0.833 + 0.512) \frac{V^2T}{gR} = 1.345 \frac{V^2T}{gR}$. The 325-ft spirals reduce the maximum rise by 6.1% (91.1 - 85.0) while the 600-ft spirals reduce the maximum rise by 11.1%.

16. Summaries of the observed superelevations and the superelevations computed from the equation $\frac{V^2T}{2gR}$ are given in tables 3 and 4. These computed values are consistently lower than the corresponding measured values. From table 3, the following comparisons of values were made: (a) the <u>maximum average of 3</u> rises in water surface ranges from 149 to 179% of $\frac{V^2T}{2gR}$, (b) the <u>total profile average</u> rise ranges from 110 to 148% of $\frac{V^2T}{2gR}$, and (c) the <u>total profile average</u> rise ranges from 73.5 to 89.5% of the <u>maximum average of 3</u> rises. From table 4, the maximum ride-up ranges from 9.73 to 47.83% of $\frac{V^2T}{2gR}$ and the average ride-up for the six tests is 32% of $\frac{V^2T}{2gR}$. Therefore, the average rise in water surface at the outside wall for the six tests is $\frac{V^2T}{2gR} + 0.32 \frac{V^2T}{2gR} = 0.66 \frac{V^2T}{gR}$ or 5.28 ft. However, the maximum rise from table 1, column 5, ranges from 4.53 to 9.4 ft. The 325-ft spirals are shorter than the length computed by $1.82 \frac{Vb}{\sqrt{gd}}$ when $T = (b + 2Sd)$, top width, while the 600-ft spirals are longer; the minimum spiral should range between 430 and 545 ft.

CONCLUSIONS

17. Use of spiral transition curves definitely minimized both transverse and longitudinal waves in the curve.

18. Minimum length of spiral should be not less than that computed by the formula $1.82 \frac{VT}{\sqrt{gd}}$ where T is the width of water surface.

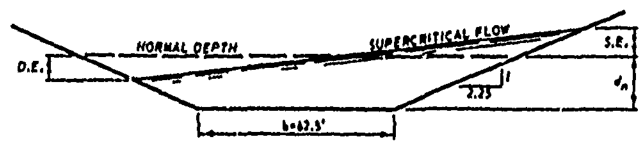
19. The 325-ft spirals reduced the amplitude of undulation only slightly, while the 600-ft spirals used for the two tests nearly eliminated the undulations entirely.

20. The 325-ft spiral is shorter than the length computed by $1.82 \frac{VT}{\sqrt{gd}}$, but the 600-ft spiral is longer.

Table 1

Summary of Test Conditions and Results

Test No.	Q, cfs	Slope	V, fps	Normal Depth ft	Froude No.	Radius ft	Curve Length ft	Spiral Length L_s, ft	Computed: Superelevation (S.E.) $\frac{V^2_T}{gR + 2TV^2}$ (1)	Computed: Superelevation (S.E.) $\frac{V^2_T}{gR}$ (2)	Computed: Depression (D.E.) $\frac{V^2_T}{gR + 2TV^2}$ (3)	Computed: Depression (D.E.) $\frac{V^2_T}{2gR}$ (4)	Test Data: Superelevation (S.E.) Above Normal Depth 1st Magnitude (5)	2nd Magnitude (6)	3rd Magnitude (7)	Average (5), (6), and (7) (8)	S.E. + D.E. Average from Table 2 (9)	Average (9) - (8) (10)	Depression (D.E.) Maximum (11)	Depression (D.E.) Minimum (12)	Measured-Computed Ratios: Superelevation (S.E.) (8) ÷ (1) (13)	Superelevation (S.E.) (8) ÷ (2) (14)	Depression (D.E.) (10) ÷ (2) (15)
											Without Spiral Transitions												
1	35,000	0.003	25.56	14.42	1.16	850	2373.65	None	3.40	3.04	2.76	1.52	3.43	2.78	2.78	3.00	3.42	0.42	1.39	-0.81†	0.882	0.987	0.138
2	45,000	0.003	27.49	16.45	1.20	850	2373.65	None	4.30	3.77	3.35	1.89	4.05	3.70	2.68	3.48	4.30	0.82	2.60	-1.05	0.810	0.923	0.218
3	35,000	0.006	32.59	12.00	1.66	850	2373.65	None	5.46	4.53	3.84	2.27	3.78	3.75	3.38	3.64	6.17	2.53	4.00	0.67	0.666	0.805	0.559
4	45,000	0.006	35.02	13.75	1.67	850	2373.65	None	7.00	5.58	4.65	2.79	4.58	4.10	4.10	4.26	6.90	[illegible]	3.10	-0.49	0.609	0.763	0.473
5	35,000	0.007	34.52	11.48	1.80	850	2373.65	None	6.16	4.98	3.84	2.49	4.10	4.02	3.89	3.99	6.90	2.91	3.93	0.48	0.648	0.802	0.584
6	45,000	0.007	37.12	13.16	1.80	850	2373.65	None	7.93	6.14	5.00	3.07	5.59	5.09	5.09	5.26	8.92	3.66	5.21	0.46	0.663	0.857	0.596
7	35,000	0.008	36.04	11.10	1.91	850	2373.65	None	7.00	5.34	4.49	2.67	4.90	4.88	4.48	4.42	8.44	4.02	4.92	-0.05	0.631	0.828	0.753
8	45,000	0.008	38.90	12.70	1.92	850	2373.65	None	8.77	6.62	5.26	3.31	5.85	5.78	5.55	5.73	9.30	3.57	5.05	0.40	0.653	0.866	0.539
9	35,000	0.009	37.78	10.70	2.04	850	2373.65	None	7.55	5.78	4.68	2.89	5.93	4.88	4.83	5.21	8.02	2.81	3.92	-0.18	0.691	0.903	0.486
10	45,000	0.009	40.79	12.25	2.06	850	2373.65	None	9.80	7.16	5.63	3.58	6.52	6.27	6.15	6.31	[illegible]	3.53	3.90	0.05	0.638	0.890	0.496
11	35,000	0.010	39.42	10.35	2.16	885	2471.40	None	7.93	5.56	4.80	2.98	6.35	6.13	5.90	6.13	9.14	3.01	4.57	-0.20	0.773	1.027	0.505
12	45,000	0.010	42.36	11.90	2.17	885	2471.40	None	11.14	7.32	5.68	3.66	7.15	6.68	6.70	6.84	11.02	4.18	4.52	-0.20	0.613	0.933	0.571
13	35,000	0.01575	[illegible]	9.10	2.71	885	2471.40	None	12.68	7.81	6.27	3.91	8.65	8.48	8.38	8.50	13.87	5.37	6.77	-0.65	0.672	1.088	0.688
14	45,000	0.01575	[illegible]	10.50	2.71	885	2471.40	None	15.70	9.55	6.86	4.78	10.88	10.30	9.90	10.36	16.97	6.61	6.17	0.25	0.660	1.085	0.692
																				Average	0.686	0.911*	0.521*
											With Spiral Transitions												
15	35,000	0.010	39.42	10.35	2.16	885	2146.54	325	7.93	5.56	4.80	2.98	4.53	4.49	4.38	4.45	7.23	2.78	3.25	1.57	0.561	0.747	0.466
16	45,000	0.010	42.36	11.90	2.17	885	2146.54	325	11.14	7.32	5.68	3.66	6.63	6.55	6.43	6.54	10.08	3.54	3.70	1.02	0.586	0.893	0.484
17	35,000	0.01575	46.39	9.10	2.71	885	2146.54	325	12.68	7.81	6.27	3.91	6.28	6.15	6.13	6.16	10.06	3.90	4.25	1.70	0.486	0.788	0.499
18	45,000	0.01575	49.76	10.50	2.71	885	2146.54	325	15.70	9.55	6.86	4.78	9.40	9.33	9.10	9.25	13.10	3.82	6.00	1.70	0.591	0.971	0.400
																				Average	0.556	0.850	
19	35,000	0.01575	46.39	9.10	2.71	885	1868.40	600	12.68	7.81	6.27	3.91	6.55	6.42	6.41	6.46	10.94	4.48	3.11	1.87	0.510	0.828	0.574
20	45,000	0.01575	49.76	10.50	2.71	885	1868.40	600	15.70	9.55	6.86	4.78	7.59	7.43	7.08	7.37	13.57	6.20	4.01	2.22	0.469	0.772	0.649
																				Average	0.490	0.800	
																					0.534	0.833**	0.512**



Note: Unit of measure for columns (1) through (12) is feet.

* $S.E. + D.E. = C \frac{V^2_T}{gR}$

$C = 0.911 + 0.521 = 1.432$

** $S.E. + D.E. = C \frac{V^2_T}{gR}$

$C = 0.833 + 0.512 = 1.345$

† Minus sign = above normal depth.

Table 2

Measured Water-Surface Differentials

	Total Superelevation (S.E. + D.E.), ft						
	1st Magnitude		2nd Magnitude		3rd Magnitude		
Test No.	Station	S.E. + D.E.	Station	S.E. + D.E.	Station	S.E. + D.E.	Average
			Without Spiral Transitions				
1	14+00	3.65	28+00	3.55	16+00	3.05	3.42
2	14+00	5.00	11+00	3.98	30+00	3.92	4.30
3	12+00	7.05	15+00	5.77	31+00	5.68	6.17
4	31+33	7.25	12+00	6.88	31+00	6.57	6.90
5	12+00	7.53	11+50	6.63	15+50	6.55	6.90
6	16+50	9.02	11+75	8.92	12+50	8.83	8.92
7	12+25	8.80	12+00	8.71	16+00	7.82	8.44
8	21+00	9.57	12+00	9.37	16+00	8.96	9.30
9	16+00	8.53	12+00	7.92	21+00	7.60	8.02
10	16+50	10.25	21+00	9.67	12+00	9.65	9.86
11	21+00	9.37	16+25	9.28	12+00	8.78	9.14
12	12+00	11.20	21+75	11.07	13+00	10.80	11.02
13	21+25	14.02	21+50	13.85	21+75	13.75	13.87
14	21+25	17.40	21+50	17.22	21+75	16.28	16.97
			With Spiral Transitions				
15	34+00	7.30	25+00	7.25	29+00	7.15	7.23
16	26+00	10.33	20+75	9.97	21+50	9.93	10.08
17	21+00	10.38	27+00	10.00	21+50	9.80	10.06
18	22+00	13.58	28+00	13.23	34+00	12.48	13.10
19	29+00	11.35	29+50	10.82	25+00	10.65	10.94
20	25+00	13.72	23+00	13.62	22+50	13.37	13.57

Table 3

Measured and Computed Superelevation, Radius = 885 Ft

Test No.	$\frac{V^2T}{gR}$ (1)	$\frac{V^2T}{2gR}$ (2)	Maximum Average of 3 Rises (3)	Total Profile Average Rise (4)	(4) ÷ (1) (5)	(4) ÷ (2) (6)	(4) ÷ (3) (7)	(3) ÷ (2) (8)
				Without Spiral				
11	5.96		6.13	3.52	59.1%		57.4%	
12	7.32		6.84	4.24	57.9%		62.0%	
13	7.81		8.50	4.88	62.5%		57.4%	
14	9.55		10.36	6.58	68.9%		63.5%	
				With Spiral				
15		2.98	4.45	3.27		1.10	73.5%	1.49
16		3.66	6.54	5.16		1.41	78.9%	1.79
19		3.91	6.46	5.78		1.48	89.5%	1.65
20		4.78	7.37	6.27		1.31	85.0%	1.54

Note: Unit of measure for columns (1) through (4) is feet.

Comparison of values between: (a) maximum average and $\frac{V^2T}{gR}$, (b) maximum average and $\frac{V^2T}{2gR}$, (c) maximum average and total profile average, and (d) total profile average and $\frac{V^2T}{2gR}$.

Without Spiral

1. The maximum average of 3 rises is nearly equal to $\frac{V^2T}{gR}$ in each test.
2. The total profile average rise ranges from 57.9 to 68.9% of $\frac{V^2T}{gR}$.
3. The total profile average rise ranges from 57.4 to 63.5% of the maximum average of 3 rises.

With Spiral

1. The maximum average of 3 rises ranges from 149 to 179% of $\frac{V^2T}{2gR}$.
2. The total profile average rise ranges from 110 to 148% of $\frac{V^2T}{2gR}$.
3. The total profile average rise ranges from 73.5 to 89.5% of the maximum average of 3 rises.

Table 4

Summary of Spiral Transition Test Conditions and Results

Test No.	Q, cfs (1)	d_n (2)	V, fps (3)	Slope (4)	Top Width (5)	$\sqrt{gd_n}$ (6)	$L_s = 1.82 \frac{VT}{\sqrt{gd_n}}$ (7)	L_s (Model) (8)
15	35,000	10.35	39.42	0.010	109.1	18.24	429	325
16	45,000	11.90	42.36	0.010	116.1	19.56	458	325
17	35,000	9.10	46.35	0.01575	103.5	17.11	510	325
18	45,000	10.50	49.76	0.01575	109.8	18.38	541	325
19	35,000	9.10	46.35	0.01575	103.5	17.11	510	600
20	45,000	10.50	49.76	0.01575	109.8	18.38	541	600

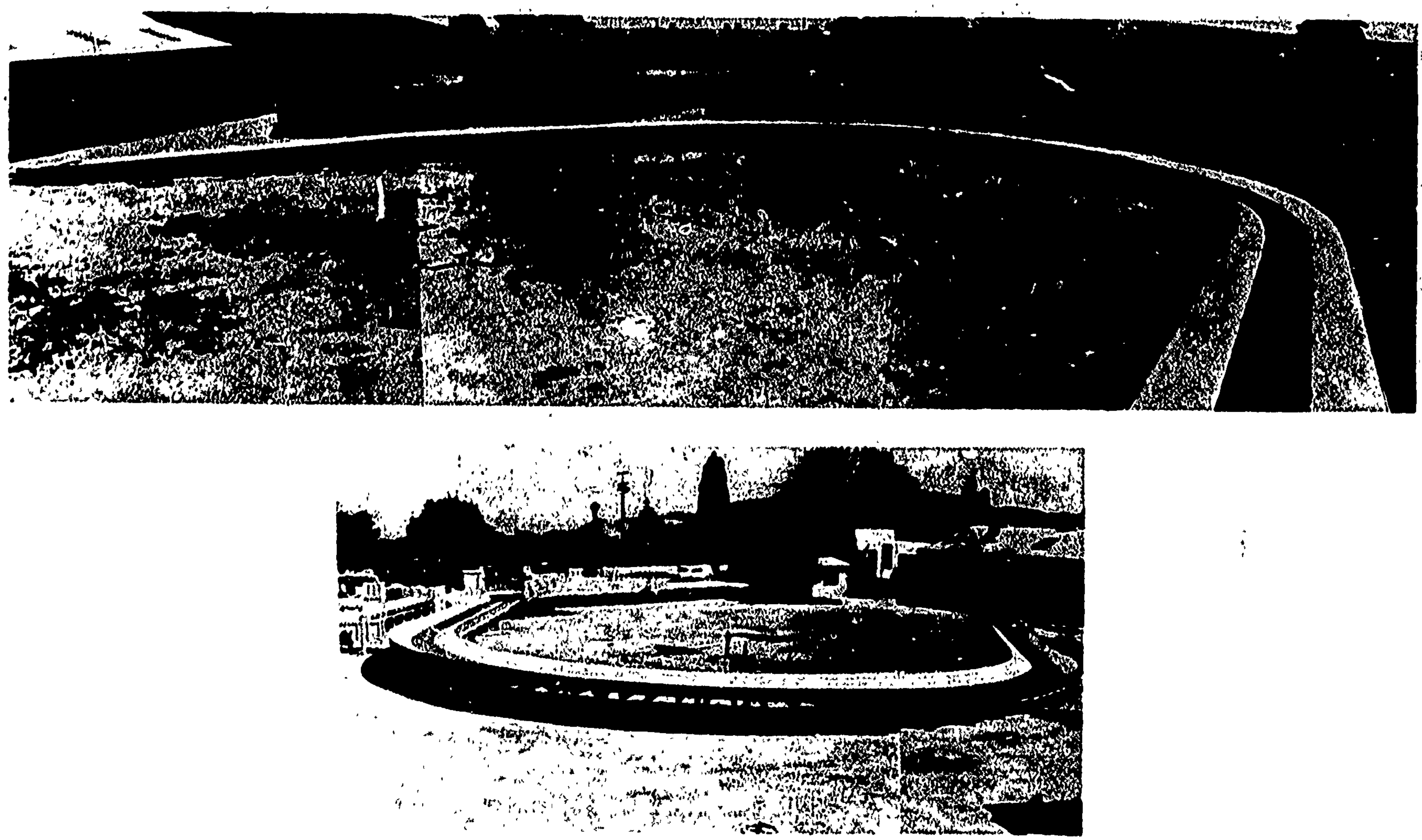
Test No.	Total Profile Average Rise (9)	$\frac{V^2T}{2gR}$ (10)	Ride-up (9) - (10) (11)	(11) ÷ (10) (12)	S.E. 1st Magnitude (13)	$0.66 \frac{V^2T}{gR}$ (14)	Difference* (15)
15	3.27	2.98	0.29	0.0973	4.53	3.93	0.60
16	5.16	3.66	1.50	0.4098	6.63	4.83	1.80
17	4.65	3.91	0.74	0.1893	6.28	5.15	1.13
18	6.56	4.78	1.78	0.3724	9.40	6.30	3.10
19	5.78	3.91	1.87	0.4783	6.55	5.15	1.40
20	6.27	4.78	1.49	0.3117	7.59	6.30	1.29
Avg	5.28	4.00	1.28	0.3200			

Note: Unit of measure for columns (2), (5), (7)-(11), and (13)-(15) is feet.

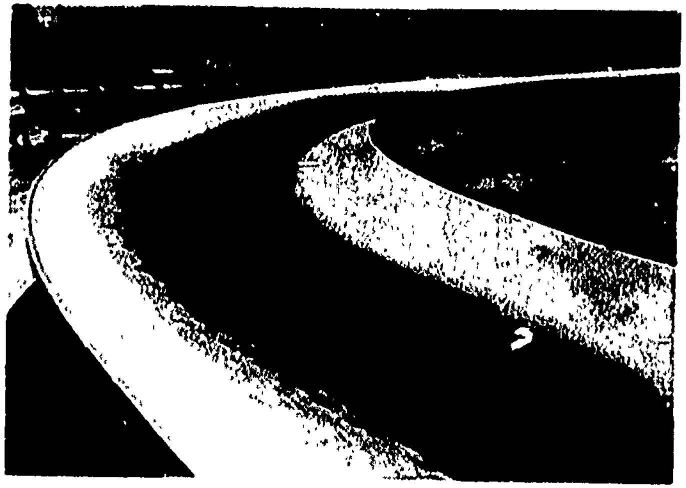
Unit of measure for column (6) is feet per second.

Minimum L_s should range between 430 and 545 ft (Col 7). The average ride-up for the six tests is $0.32 \frac{V^2T}{2gR}$ (Col 12). The average rise in water surface at the outside wall is $\frac{V^2T}{2gR} + 0.32 \frac{V^2T}{2gR} = 0.66 \frac{V^2T}{gR} = 5.28$ ft (Col 14).

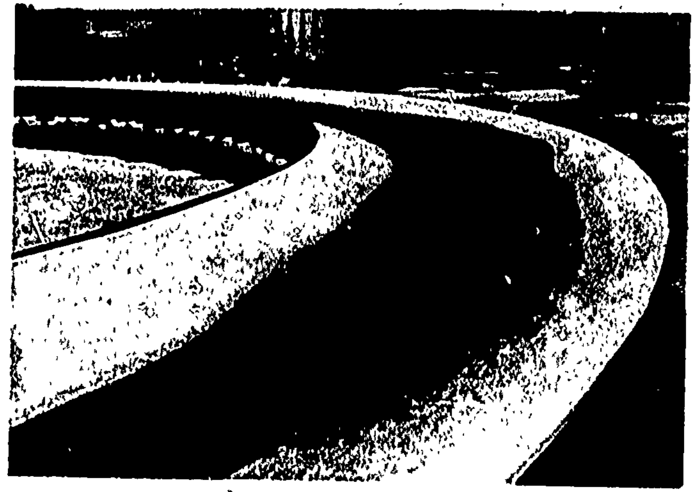
* These differences would be within the normal freeboard allowance except test 18 where the spiral was too short. The length, L_s, was based on b instead of T in $1.82 \frac{VT}{\sqrt{gd}}$.



Photograph 1. General views of the 1:25-scale model



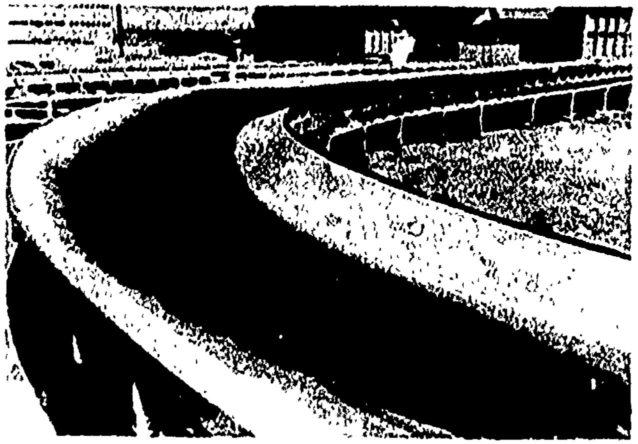
Upstream, right side at sta 31+00



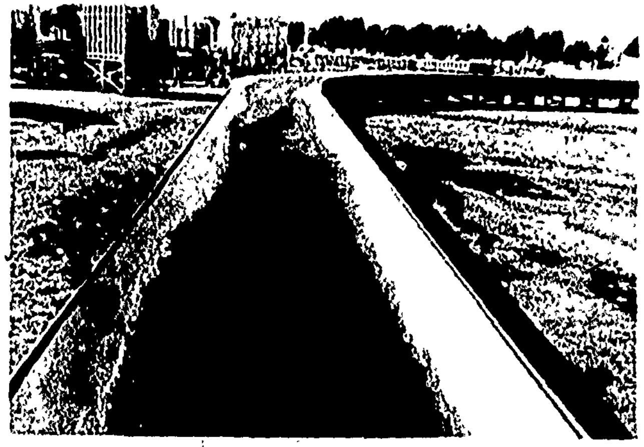
Downstream, right side at sta 20+00

Downstream, right side at sta 38+00

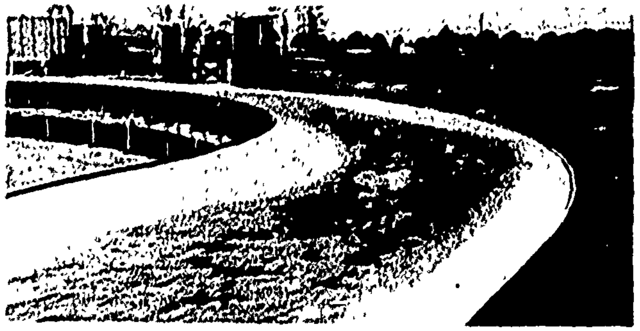
Photograph 2. Flow conditions; simple curve, S = 0.01575, discharge 35,000 cfs



Upstream, right side at sta 31+00



Upstream, centerline at end of model

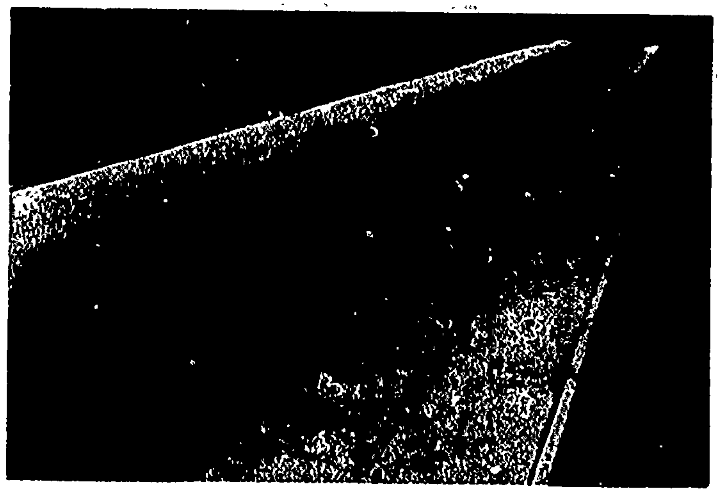


Downstream, right side at sta 15+00

Downstream, right side at sta 31+00

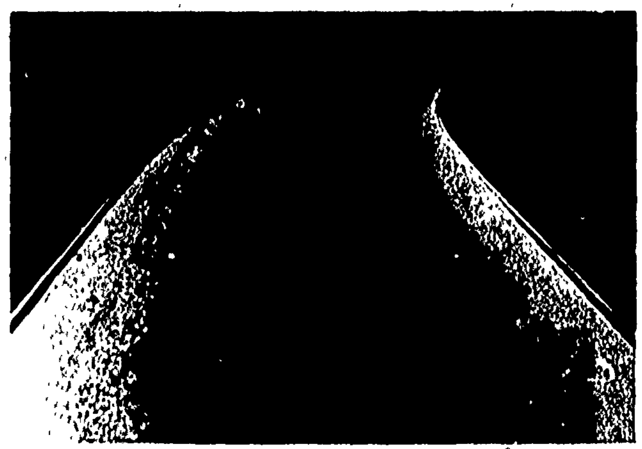
Photograph 3. Flow conditions; simple curve, $S = 0.01575$, discharge 45,000 cfs

Downstream, right side at sta 38+00

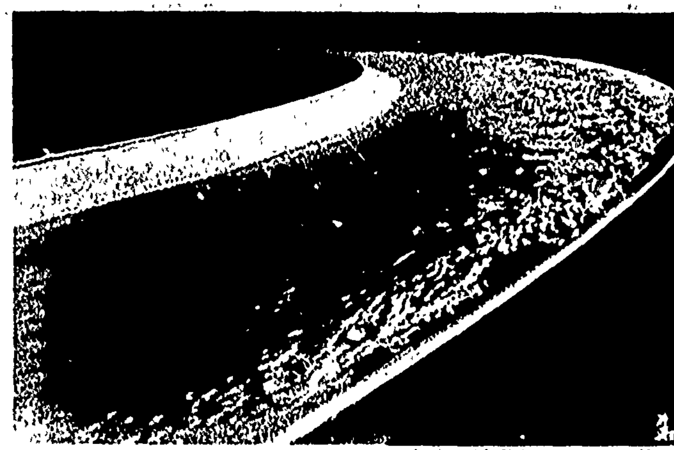


Downstream, right side at sta 44+00

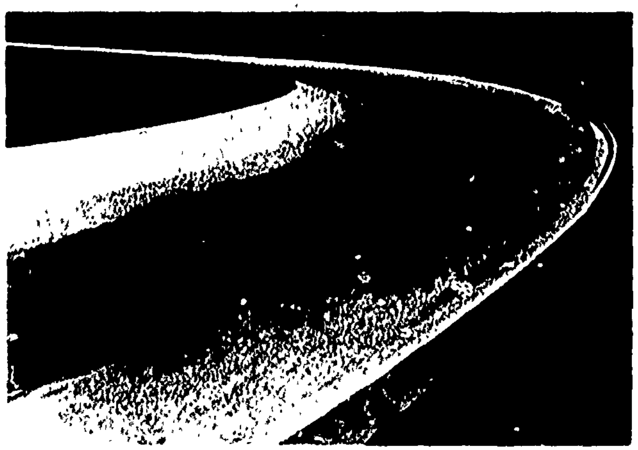
Photograph 4. Test 18 flow conditions; L_s = 325 ft, S = 0.010, discharge 35,000 cfs



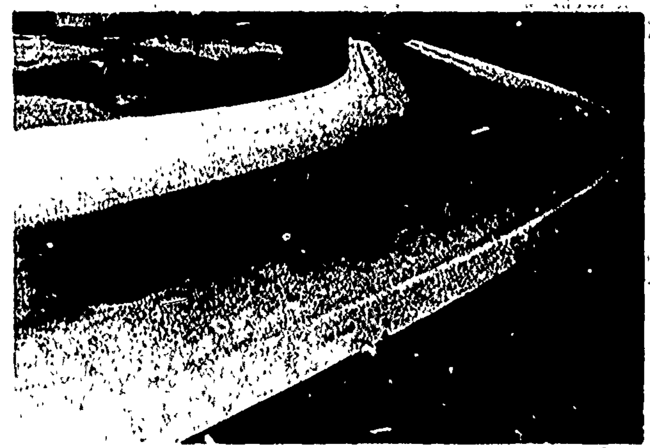
Upstream, sta 48+00



Downstream, right side at sta 28+50

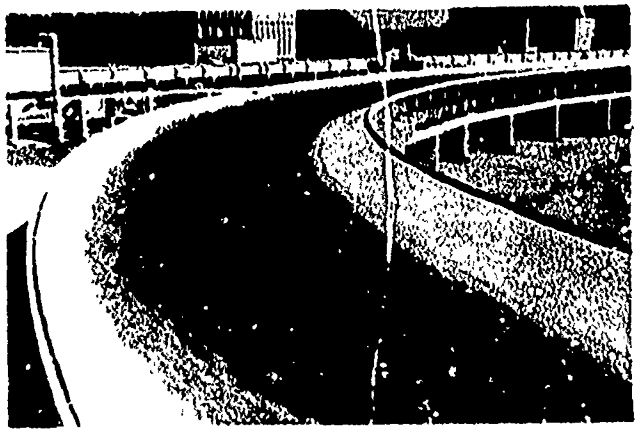


Downstream, right side at sta 32+00

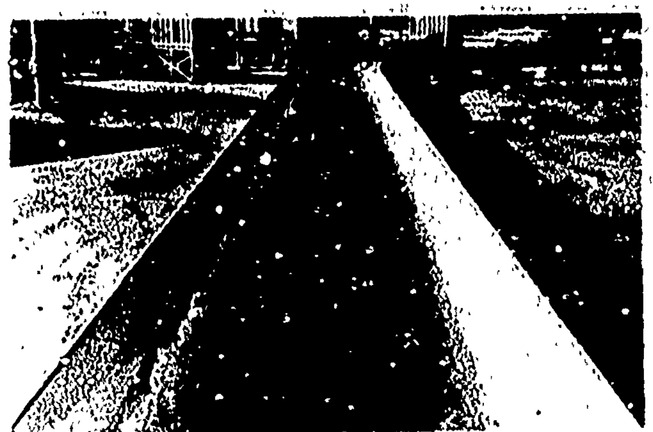


Downstream, right side at sta 38+00

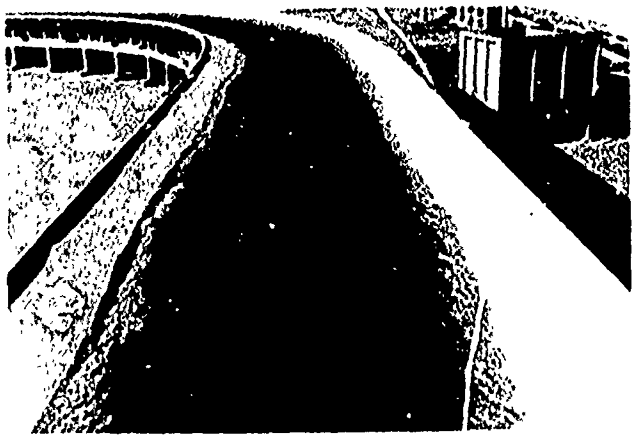
Photograph 5. Test 18 flow conditions; L_s = 325 ft, S = 0.010, discharge 45,000 cfs



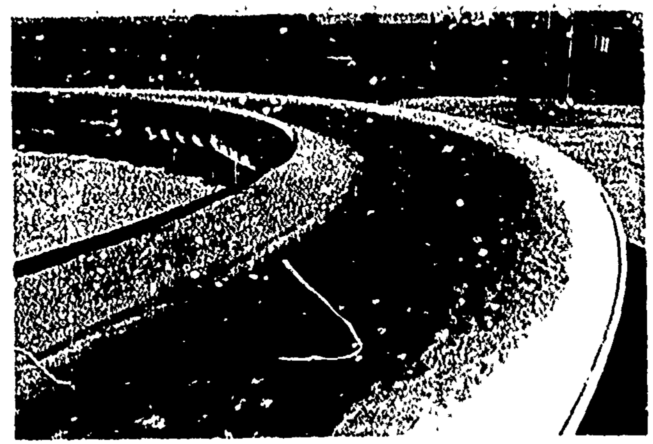
Upstream, right side at sta 31+00



Upstream from end of model

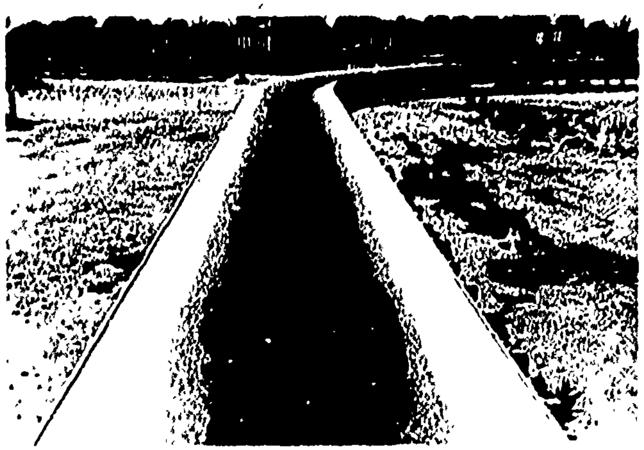


Downstream, centerline of channel at sta 10+00



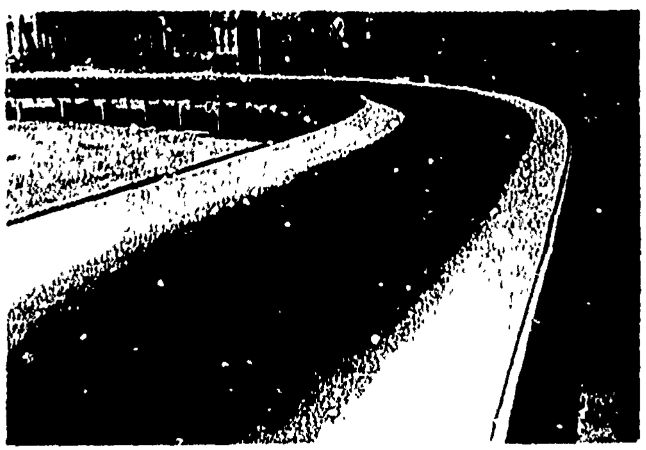
Downstream, right side at sta 20+00

Photograph 6. Flow conditions; L_s = 600 ft, S = 0.01575, discharge 35,000 cfs

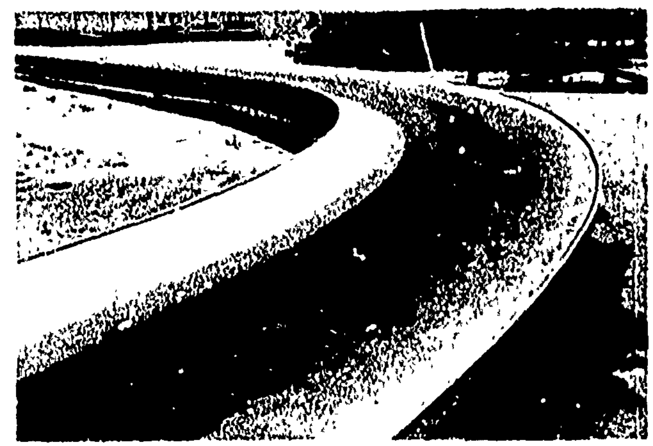


Upstream from end of model

Upstream, right side at sta 45+00

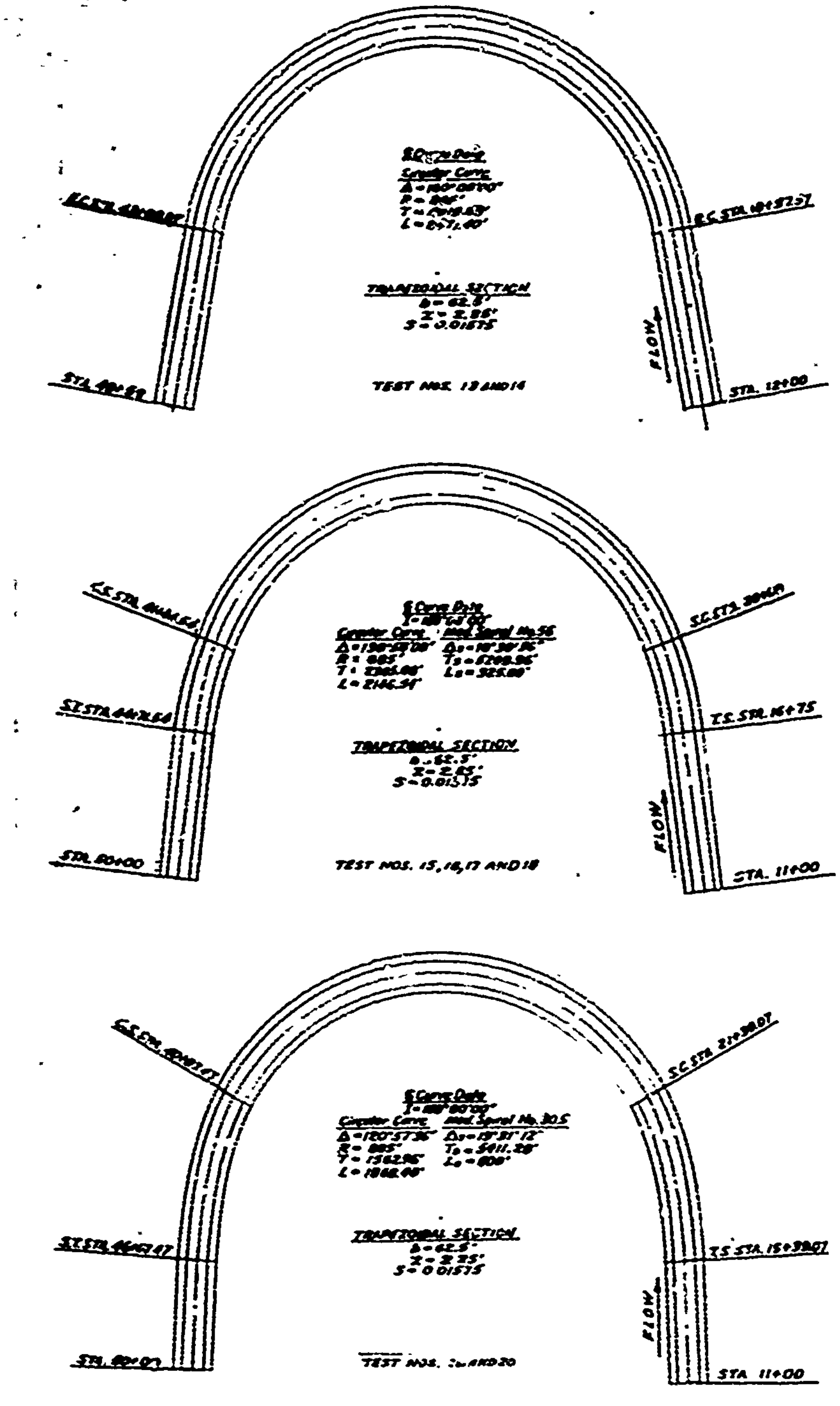


Downstream, right side at sta 13+00



Downstream, right side at sta 30+00

Photograph 7. Flow conditions; L_s = 600 ft, S = 0.01575, discharge 45,000 cfs



PLAN OF TEST CHANNEL FOR TEST NOS. 13, 14, 15, 16, 17, 18, 19, AND 20

PLATE I

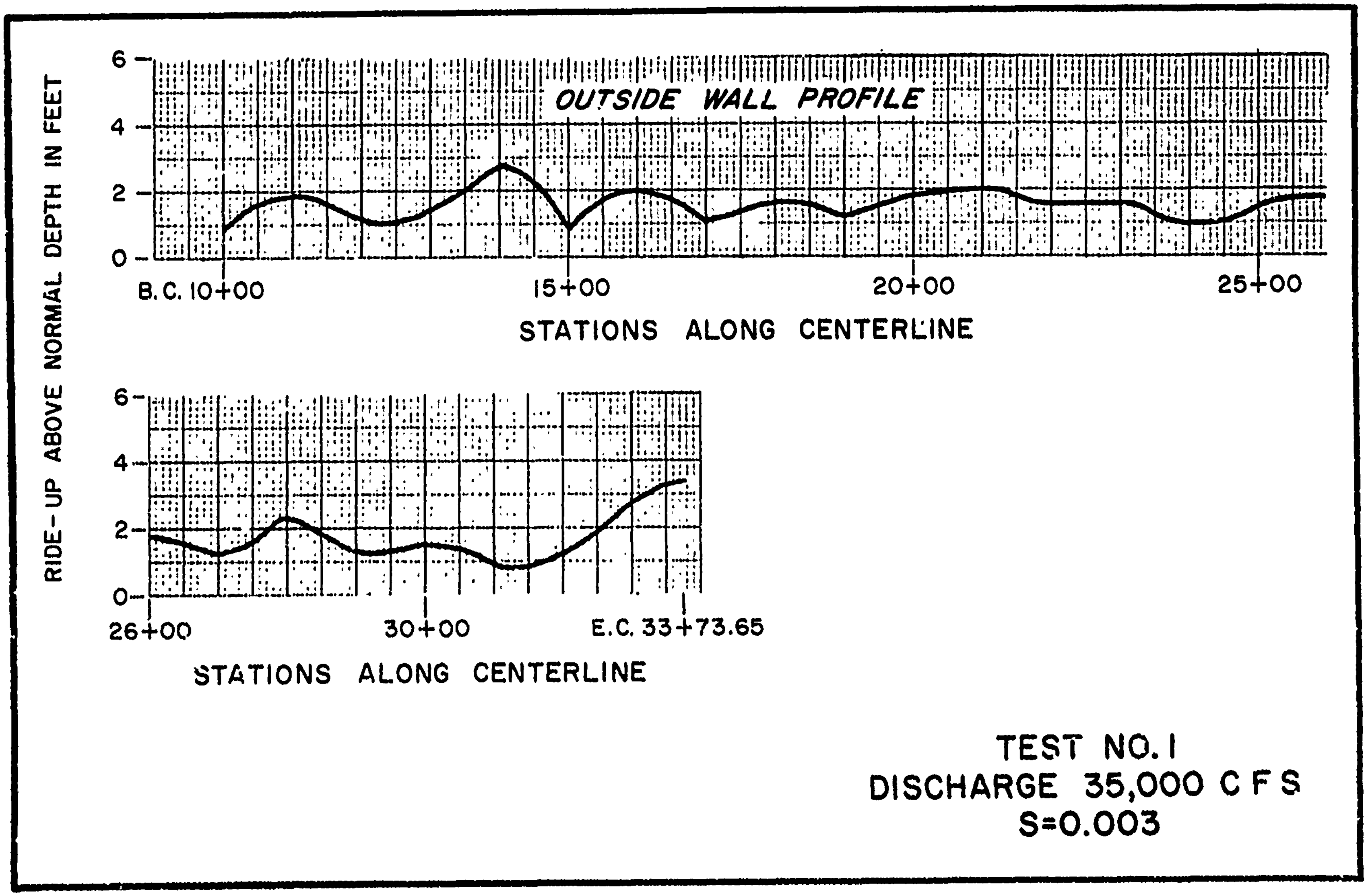

OUTSIDE WALL PROFILE
RIDE-UP ABOVE NORMAL DEPTH IN FEET
0
2
4
6
B.C. 10+00
15+00
20+00
25+00
STATIONS ALONG CENTERLINE
26+00
30+00
E.C. 33+73.65
STATIONS ALONG CENTERLINE
TEST NO. 1
DISCHARGE 35,000 C F S
S=0.003

PLATE 2

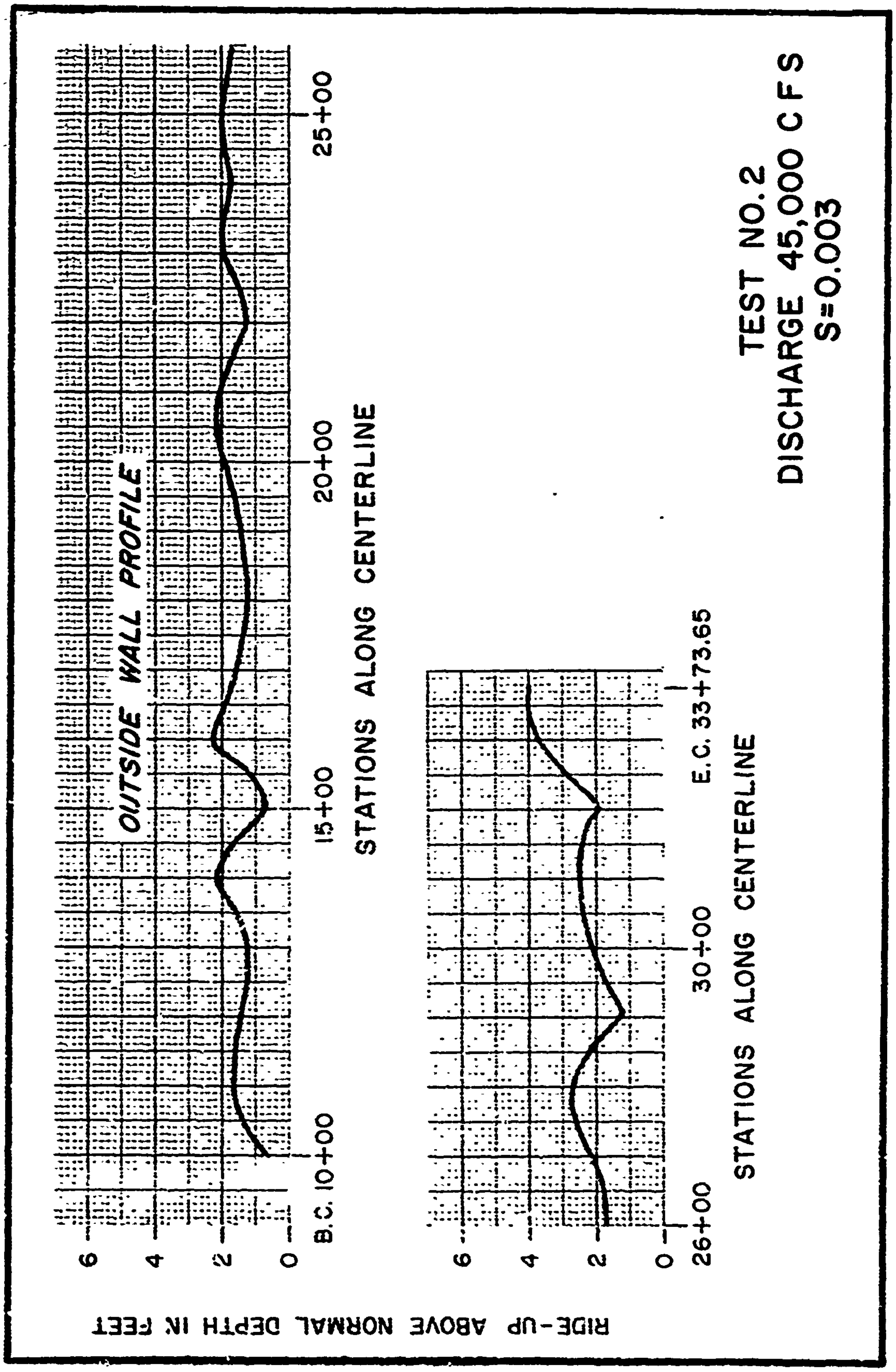

OUTSIDE WALL PROFILE
RIDE-UP ABOVE NORMAL DEPTH IN FEET
0
2
4
6
B.C. 10+00
15+00
20+00
25+00
STATIONS ALONG CENTERLINE
26+00
30+00
E.C. 33+73.65
STATIONS ALONG CENTERLINE
TEST NO. 2
DISCHARGE 45,000 C F S
S=0.003

PLATE 3

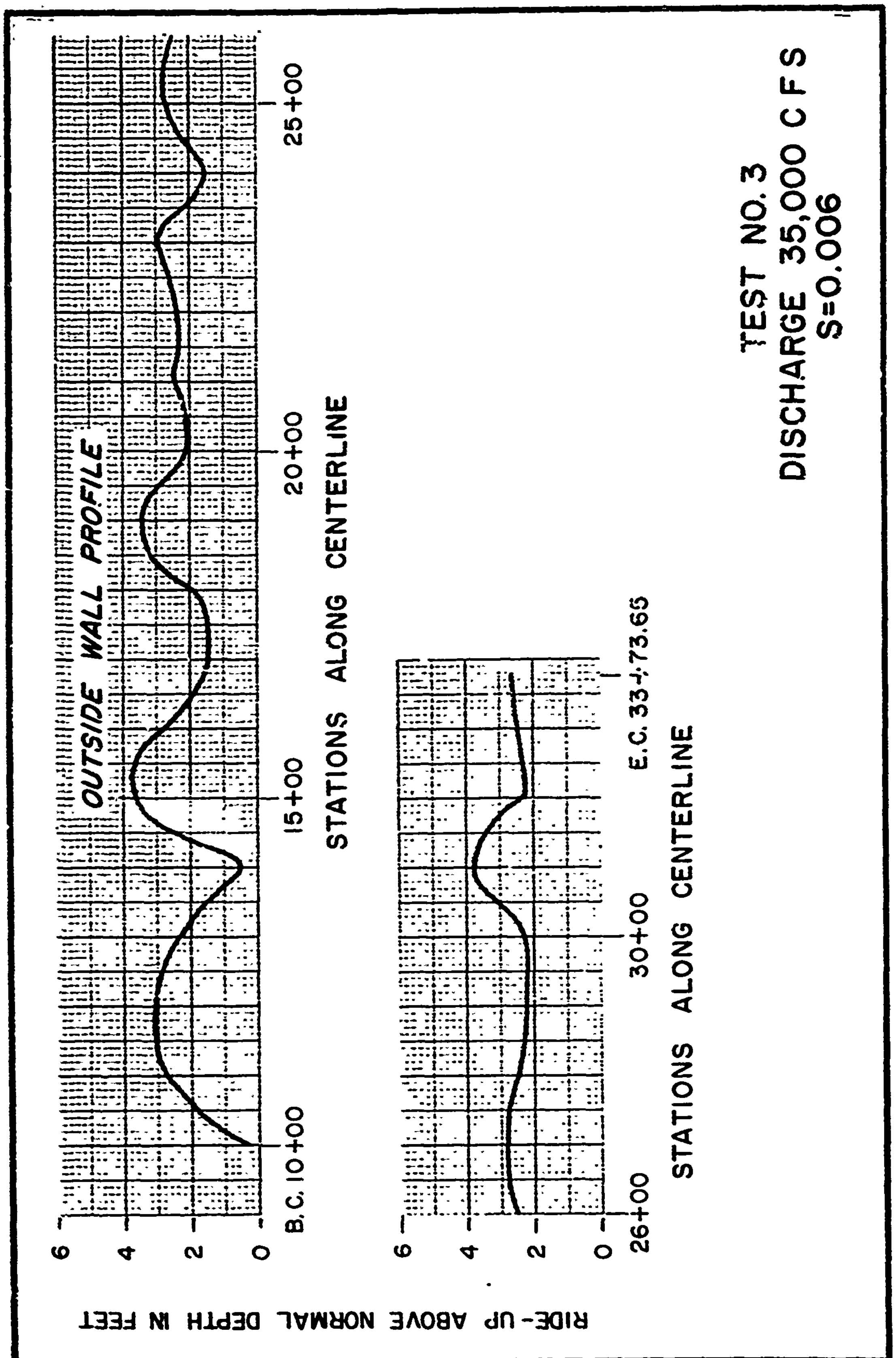
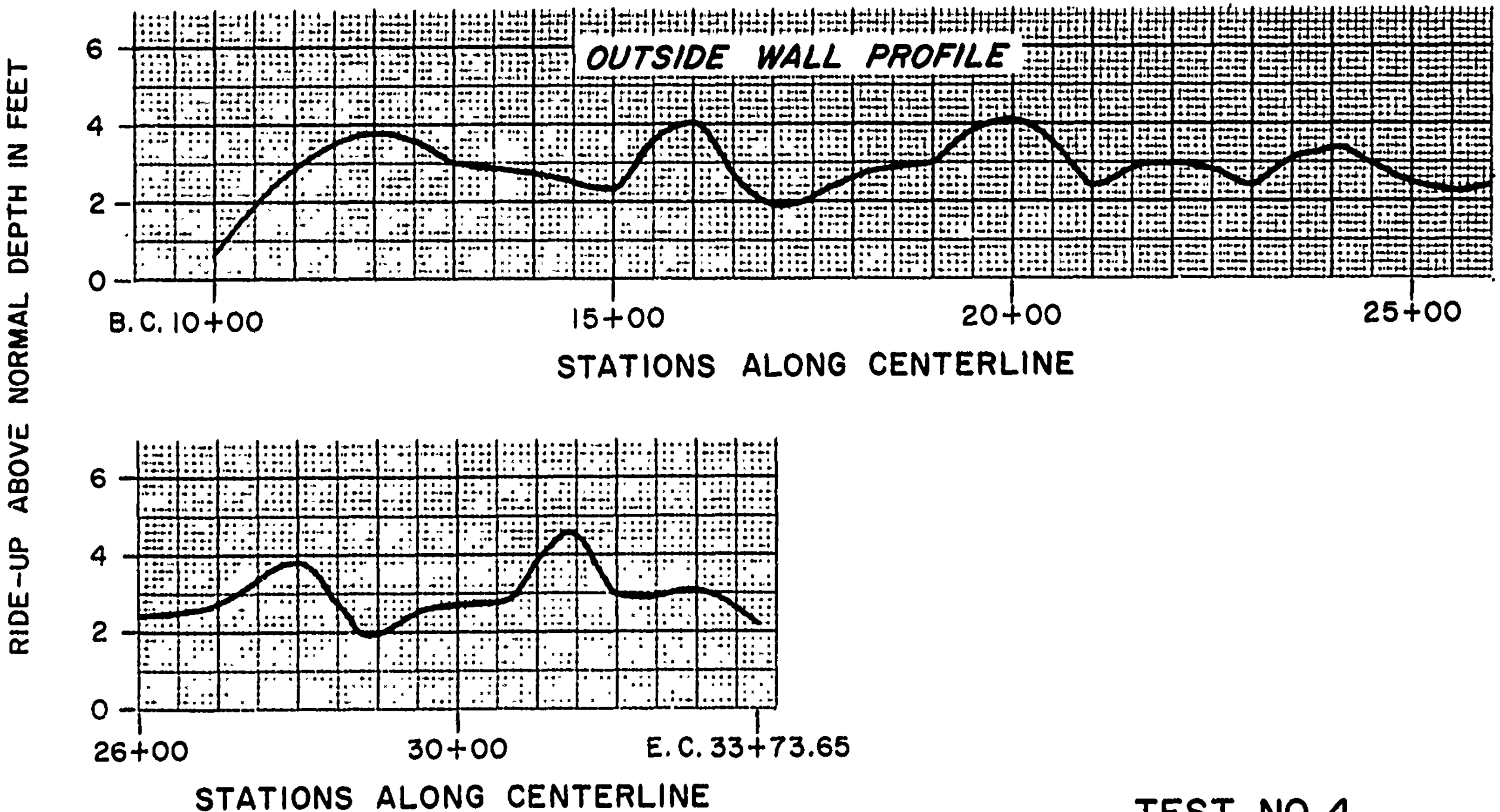

TEST NO. 3
DISCHARGE 35,000 C F S
S=0.006
OUTSIDE WALL PROFILE
RIDE-UP ABOVE NORMAL DEPTH IN FEET
0
2
4
6
B.C. 10+00
15+00
20+00
25+00
STATIONS ALONG CENTERLINE
26+00
30+00
E.C. 33+73.65
STATIONS ALONG CENTERLINE

PLATE 4



TEST NO. 4
DISCHARGE 45,000 C F S
S=0.006

PLATE 5

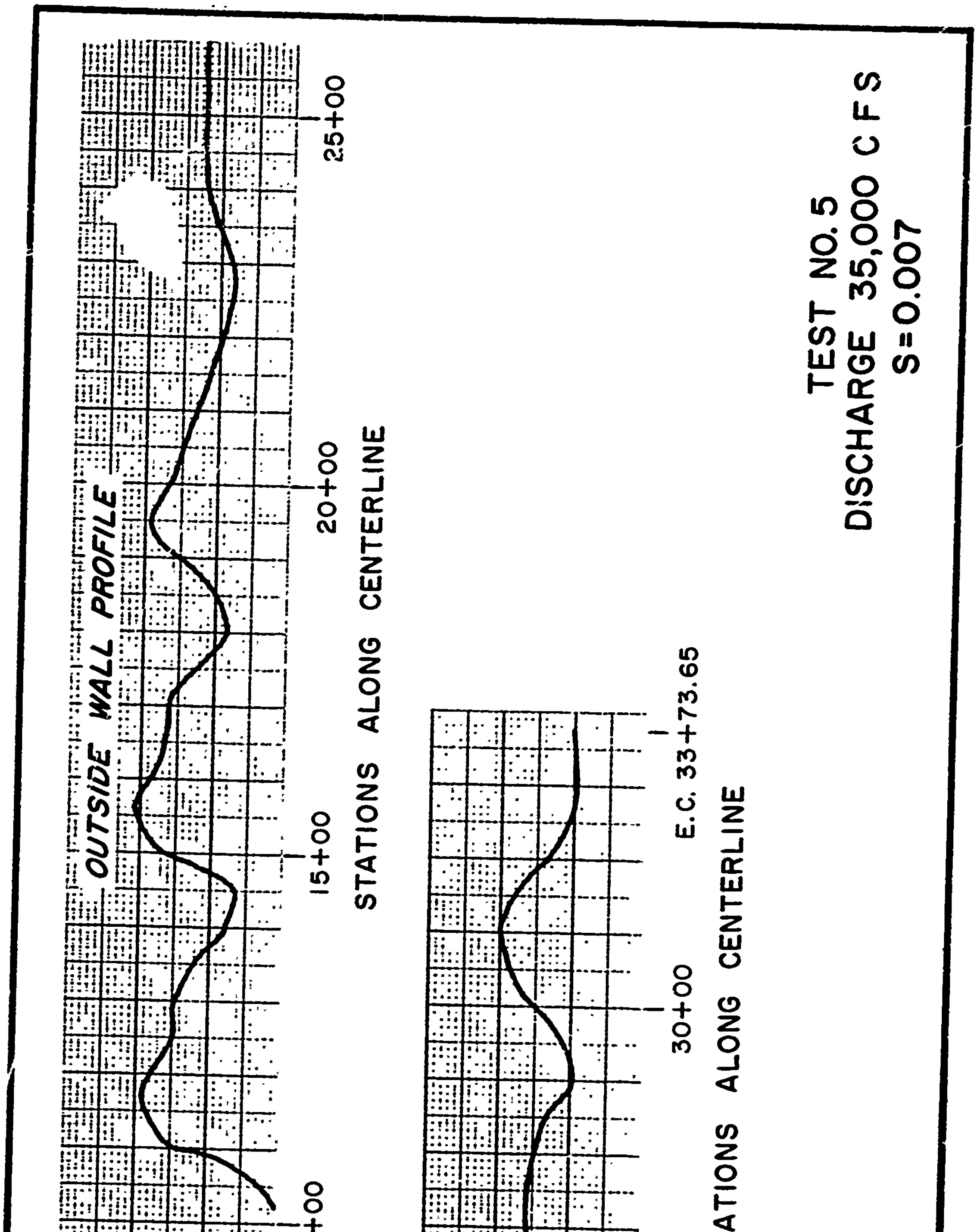

OUTSIDE WALL PROFILE
RIDE-UP ABOVE NORMAL DEPTH IN FEET
0
2
4
6
B.C. 10+00
15+00
20+00
25+00
STATIONS ALONG CENTERLINE
26+00
30+00
E.C. 33+73.65
STATIONS ALONG CENTERLINE
TEST NO. 5
DISCHARGE 35,000 C F S
S=0.007

PLATE 6

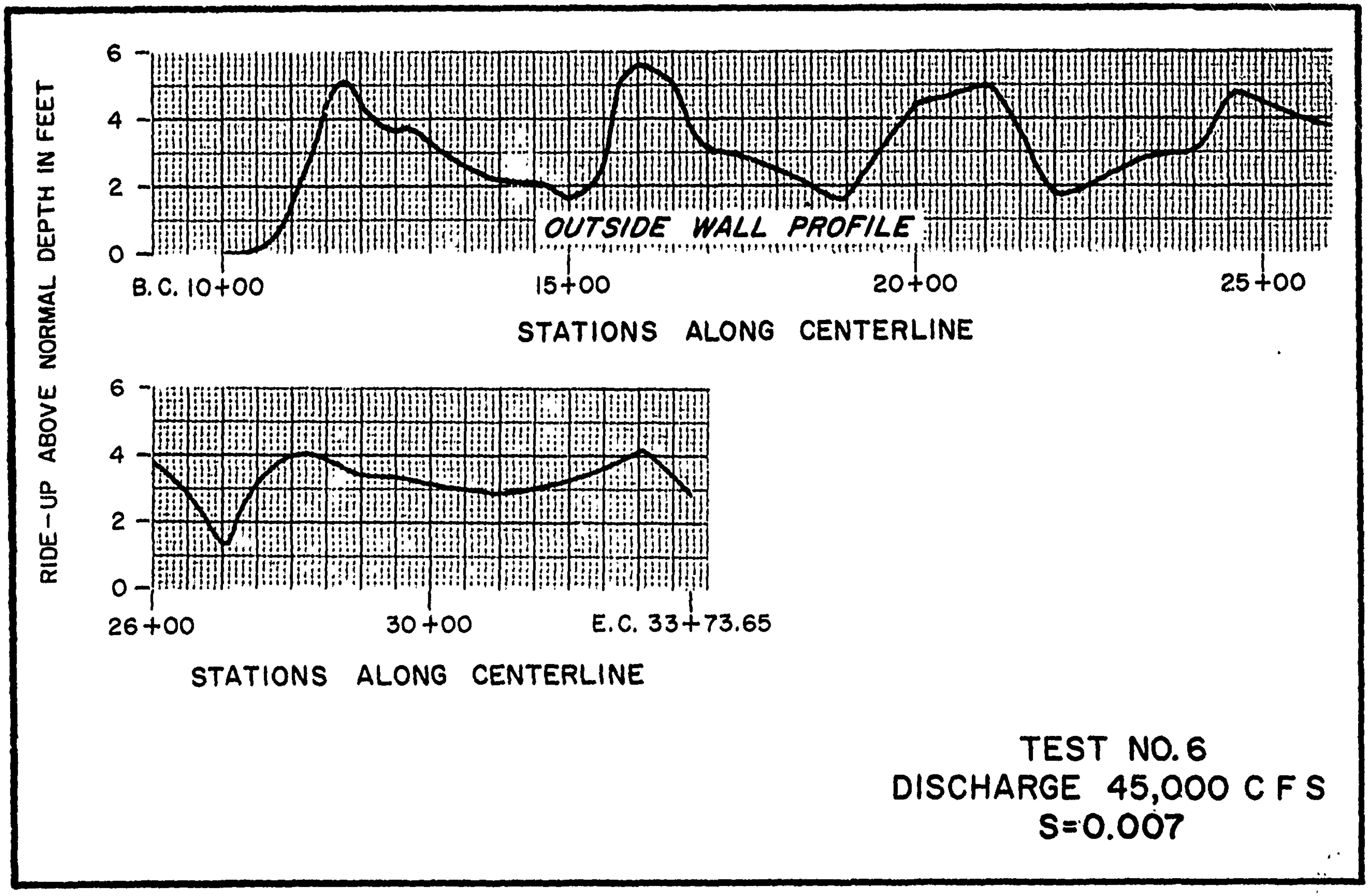

RIDE-UP ABOVE NORMAL DEPTH IN FEET
6
4
2
0
OUTSIDE WALL PROFILE
B.C. 10+00
15+00
20+00
25+00
STATIONS ALONG CENTERLINE
26+00
30+00
E.C. 33+73.65
STATIONS ALONG CENTERLINE
TEST NO. 6
DISCHARGE 45,000 C F S
S=0.007

PLATE 7

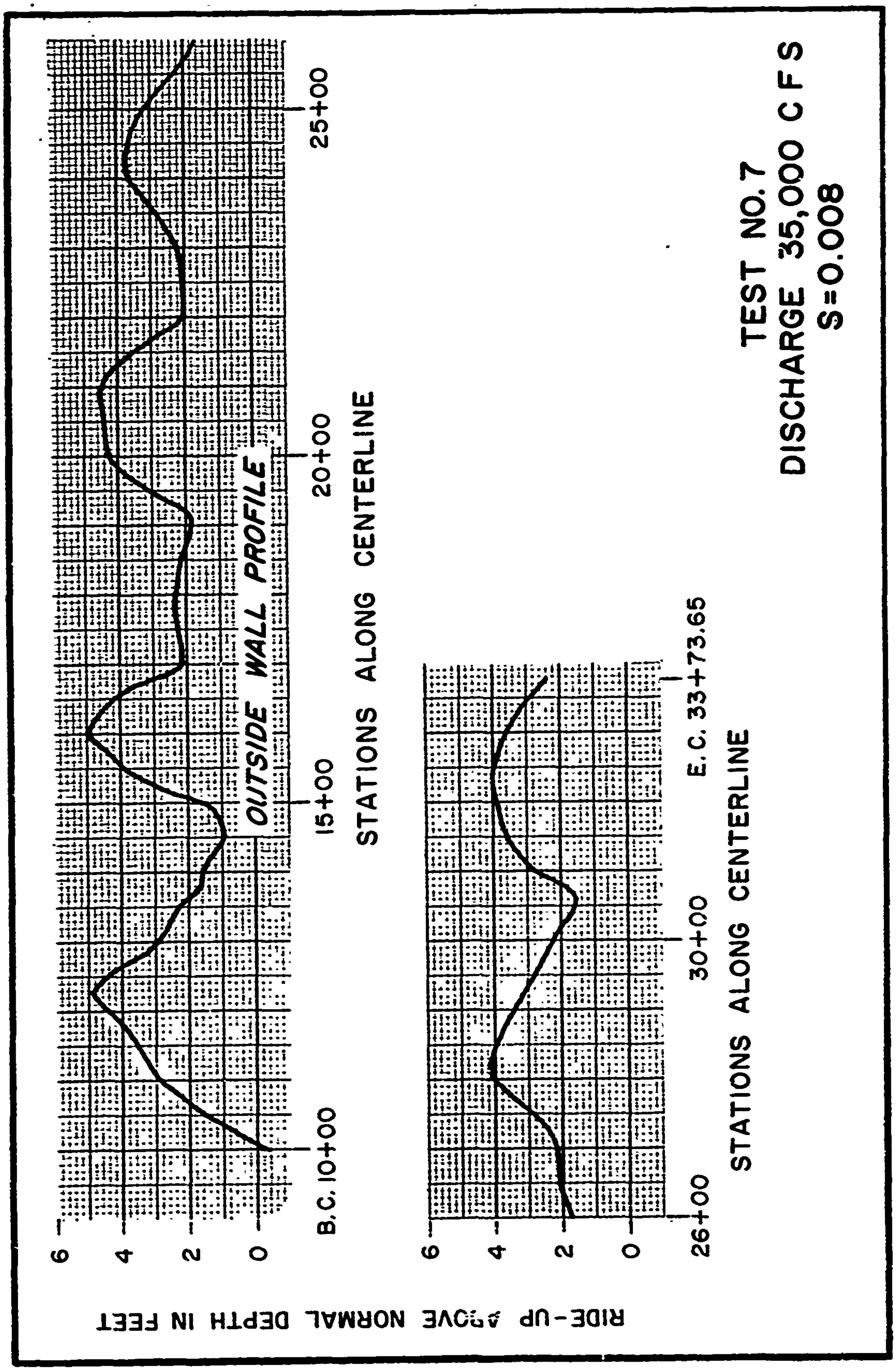

TEST NO. 7
DISCHARGE 35,000 C F S
S=0.008
OUTSIDE WALL PROFILE
RIDE-UP ABOVE NORMAL DEPTH IN FEET
0
2
4
6
B.C. 10+00
15+00
20+00
25+00
STATIONS ALONG CENTERLINE
26+00
30+00
E.C. 33+73.65
STATIONS ALONG CENTERLINE

PLATE 8

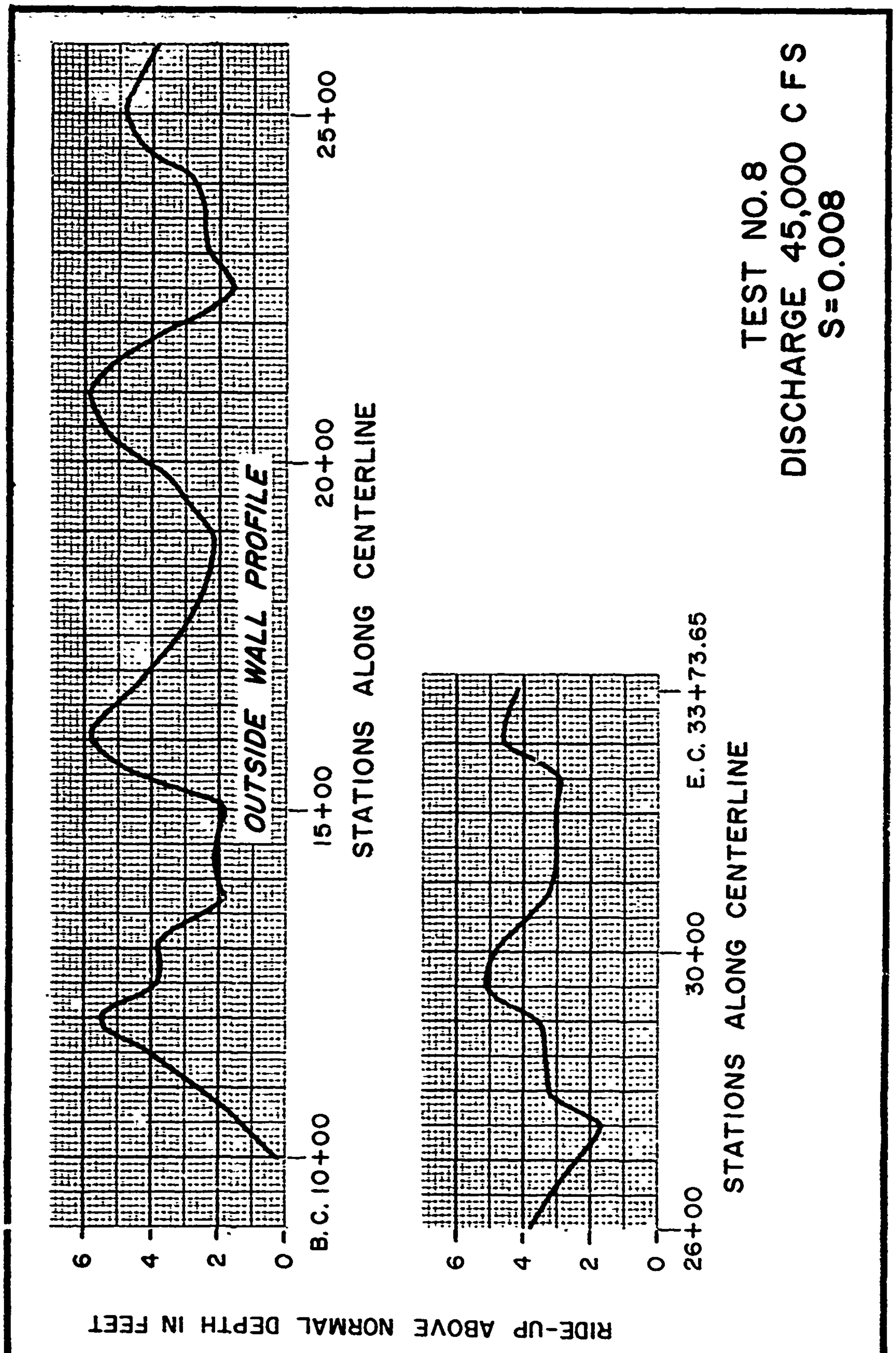

TEST NO. 8
DISCHARGE 45,000 C F S
S=0.008
OUTSIDE WALL PROFILE
RIDE-UP ABOVE NORMAL DEPTH IN FEET
STATIONS ALONG CENTERLINE
B.C. 10+00
15+00
20+00
25+00
26+00
30+00
E.C. 33+73.65
0
2
4
6

PLATE 9

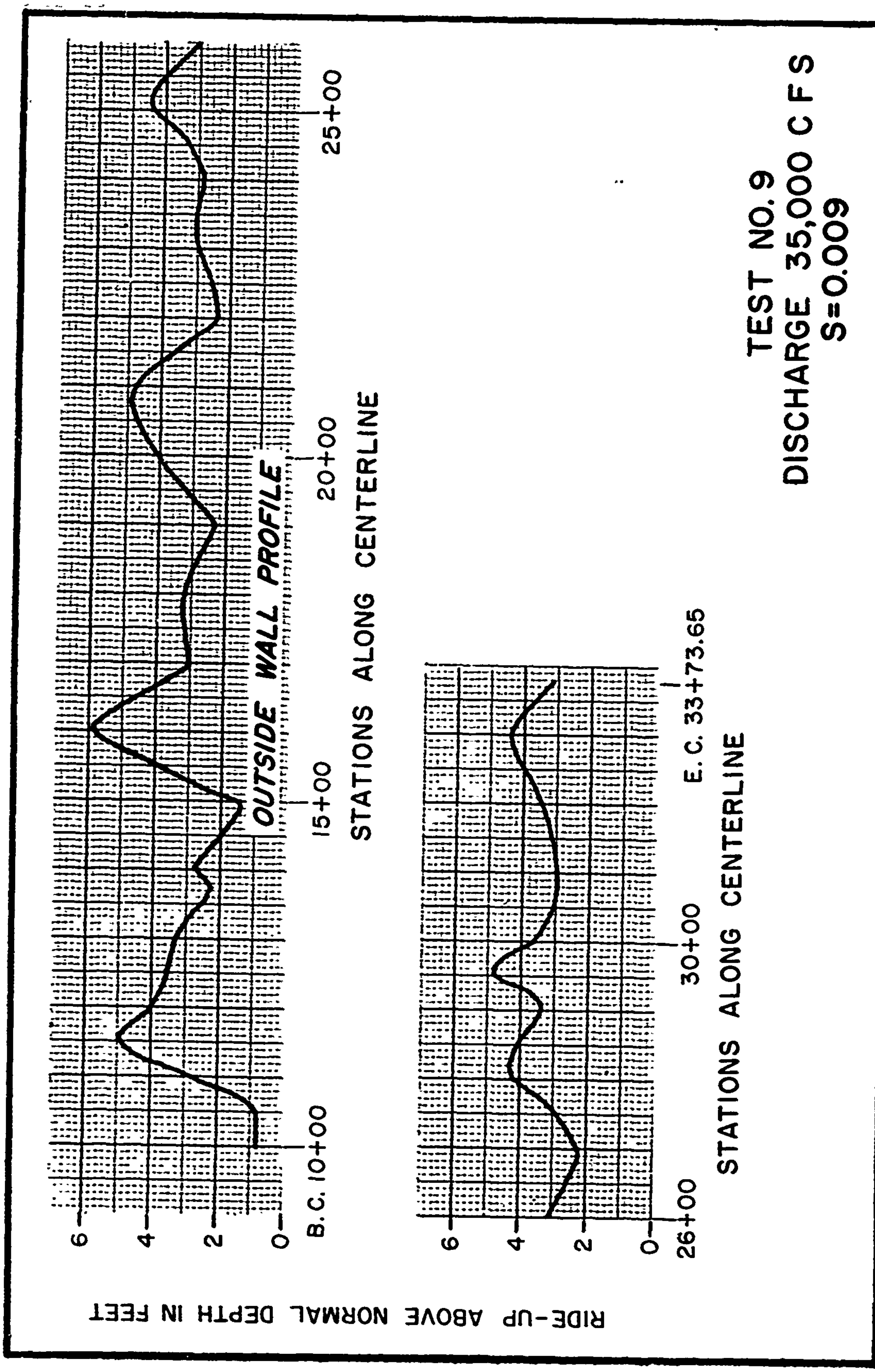

OUTSIDE WALL PROFILE
RIDE-UP ABOVE NORMAL DEPTH IN FEET
0
2
4
6
B.C. 10+00
15+00
20+00
25+00
STATIONS ALONG CENTERLINE
26+00
30+00
E. C. 33+73.65
STATIONS ALONG CENTERLINE
TEST NO. 9
DISCHARGE 35,000 C F S
S=0.009

PLATE 10

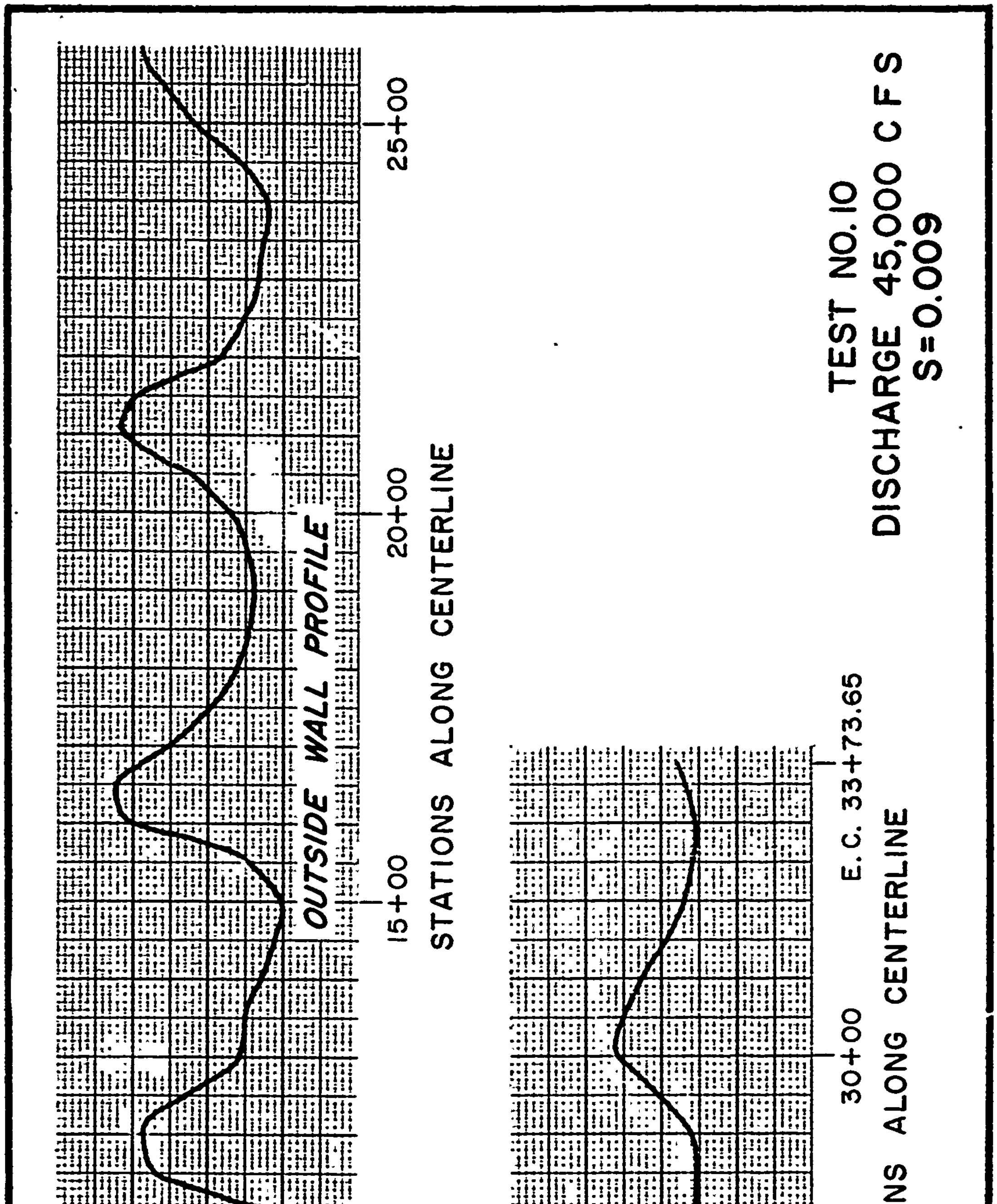

TEST NO. 10
DISCHARGE 45,000 C F S
S=0.009
OUTSIDE WALL PROFILE
RIDE-UP ABOVE NORMAL DEPTH IN FEET
STATIONS ALONG CENTERLINE
B.C. 10+00
15+00
20+00
25+00
26+00
30+00
E.C. 33+73.65
0
2
4
6
8

PLATE II

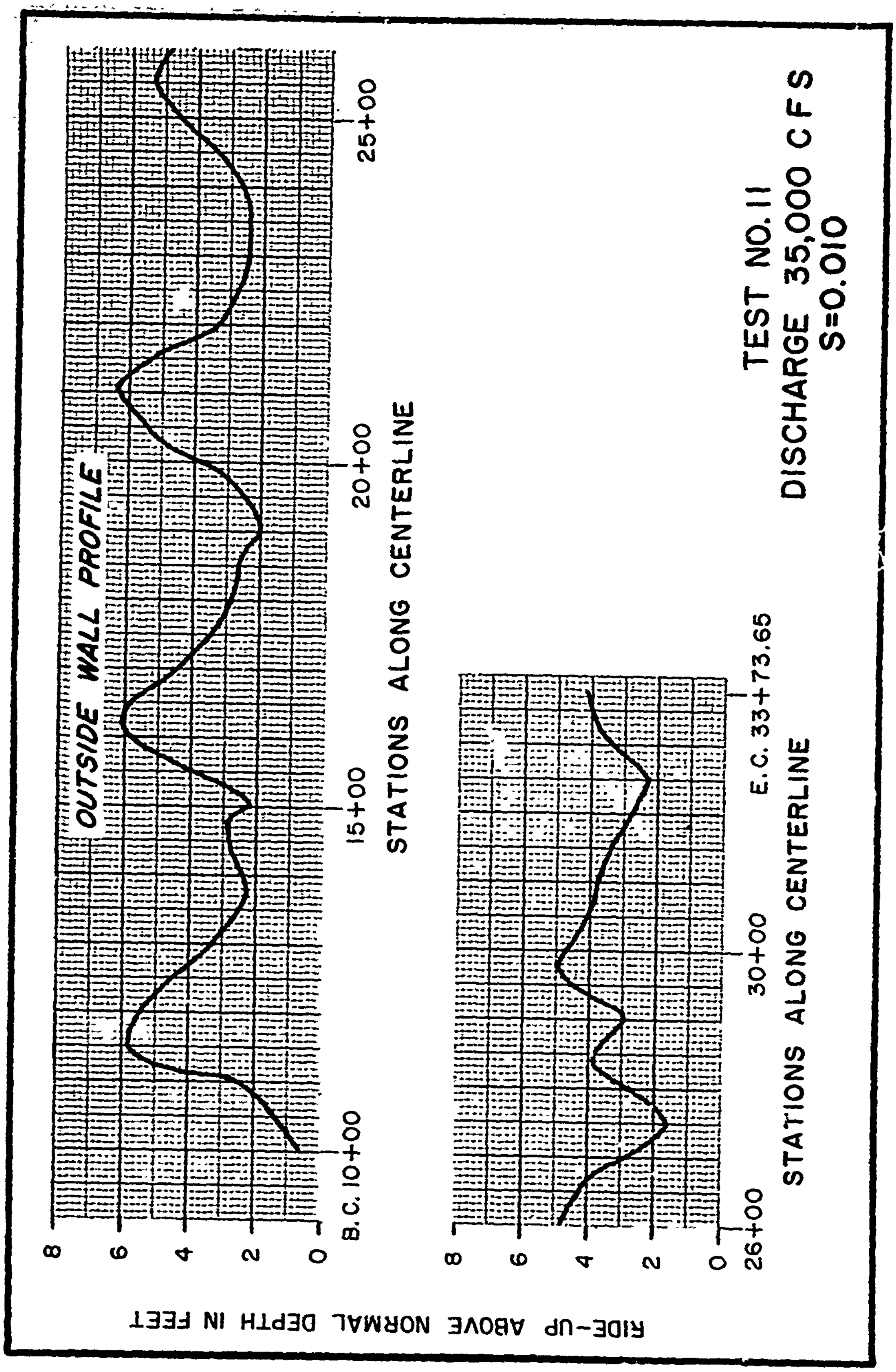

OUTSIDE WALL PROFILE
RIDE-UP ABOVE NORMAL DEPTH IN FEET
0
2
4
6
8
B.C. 10+00
15+00
20+00
25+00
STATIONS ALONG CENTERLINE
26+00
30+00
E.C. 33+73.65
STATIONS ALONG CENTERLINE
TEST NO. 11
DISCHARGE 35,000 CFS
S=0.010

PLATE 12

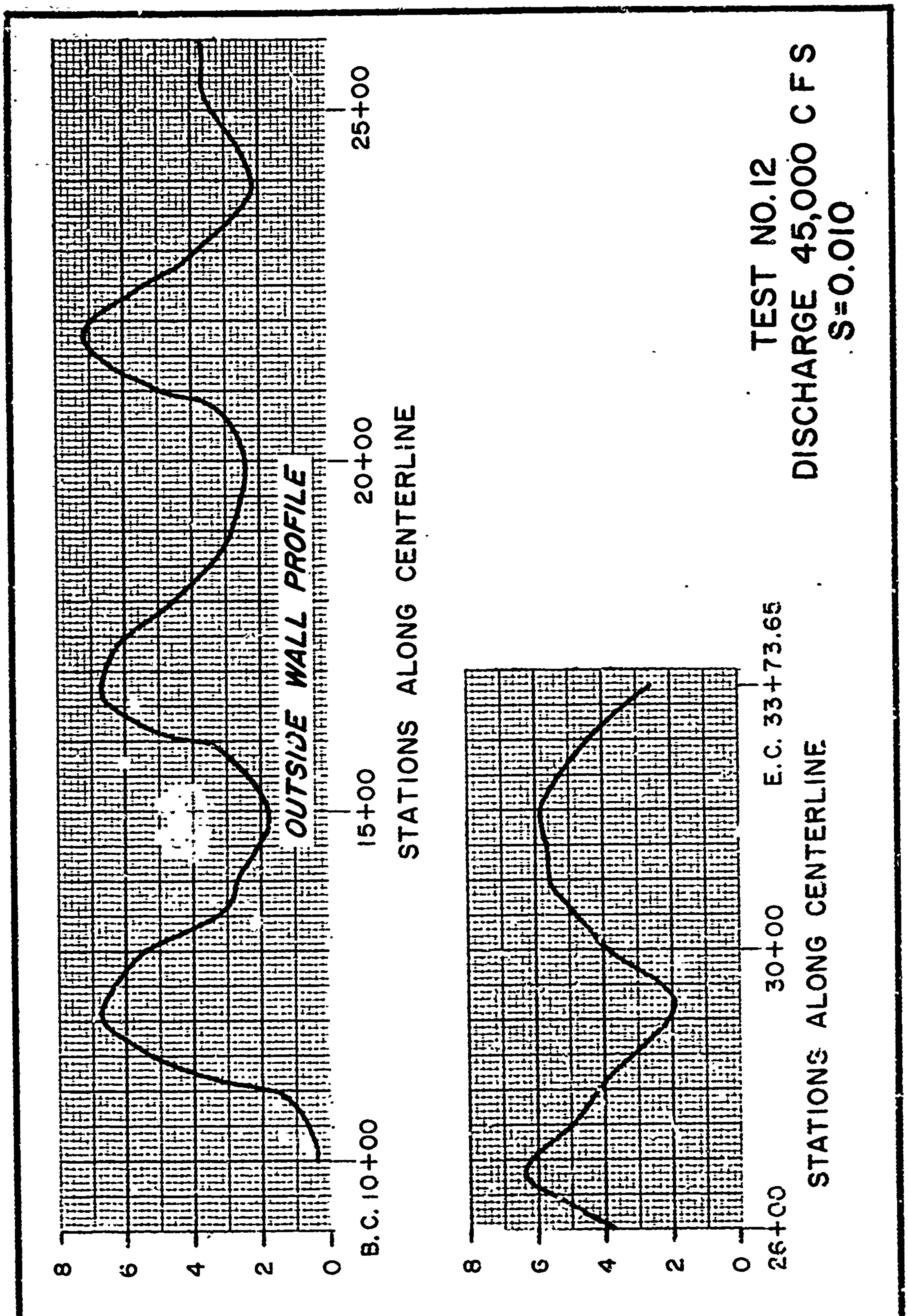

TEST NO.12
DISCHARGE 45,000 C F S
S=0.010
OUTSIDE WALL PROFILE
RIDE-UP ABOVE NORMAL DEPTH IN FEET
STATIONS ALONG CENTERLINE
B.C. 10+00
15+00
20+00
25+00
26+00
30+00
E.C. 33+73.65
0
2
4
6
8

PLATE 13

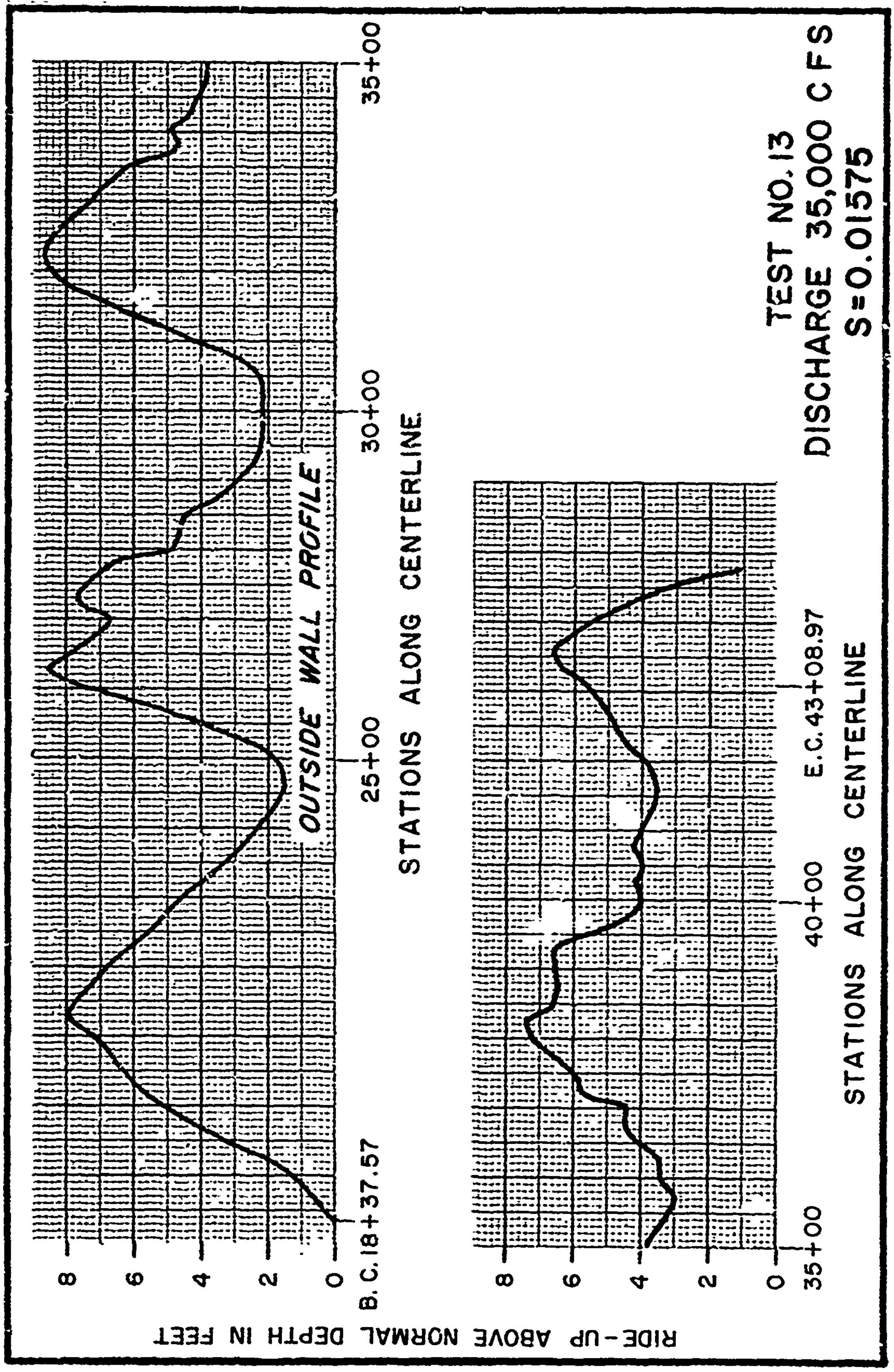

OUTSIDE WALL PROFILE
RIDE-UP ABOVE NORMAL DEPTH IN FEET
0
2
4
6
8
B.C. 18+37.57
25+00
30+00
35+00
STATIONS ALONG CENTERLINE
35+00
40+00
E.C. 43+08.97
STATIONS ALONG CENTERLINE
TEST NO. 13
DISCHARGE 35,000 CFS
S=0.01575

PLATE 14

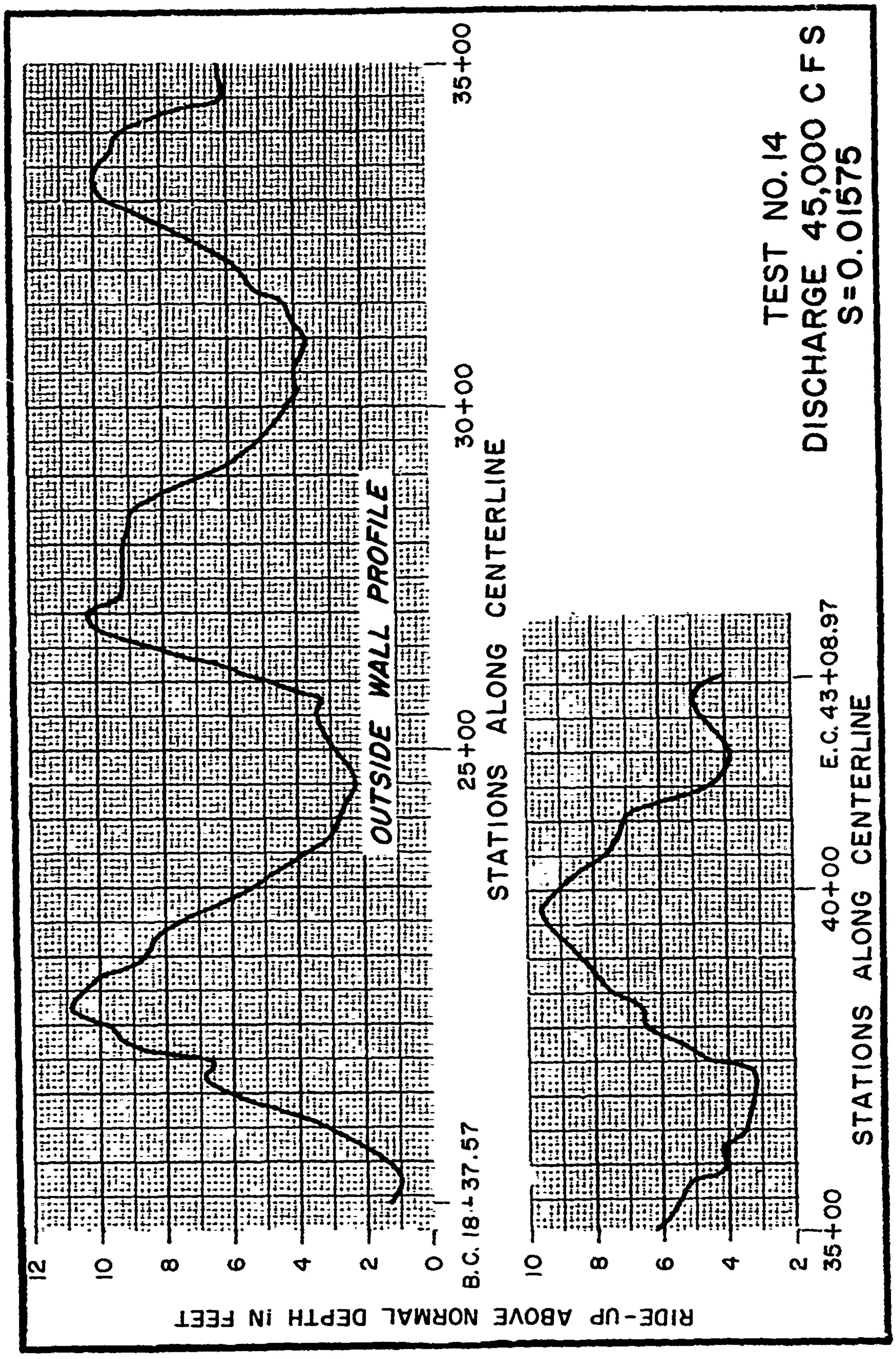
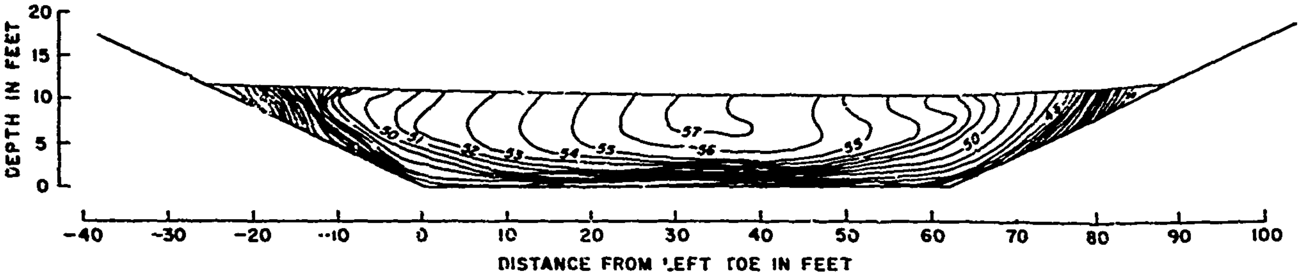
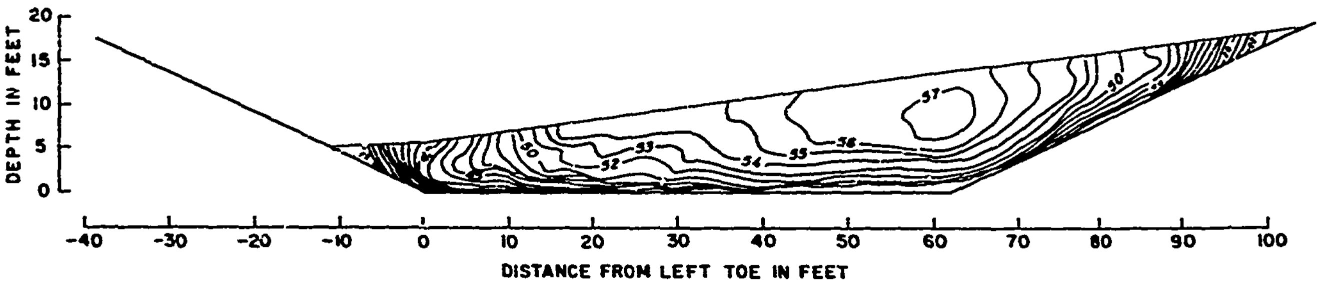

OUTSIDE WALL PROFILE
RIDE-UP ABOVE NORMAL DEPTH IN FEET
12
10
8
6
4
2
0
B.C. 18+37.57
25+00
30+00
35+00
STATIONS ALONG CENTERLINE
10
8
6
4
2
35+00
40+00
E.C. 43+08.97
STATIONS ALONG CENTERLINE
TEST NO. 14
DISCHARGE 45,000 C F S
S=0.01575

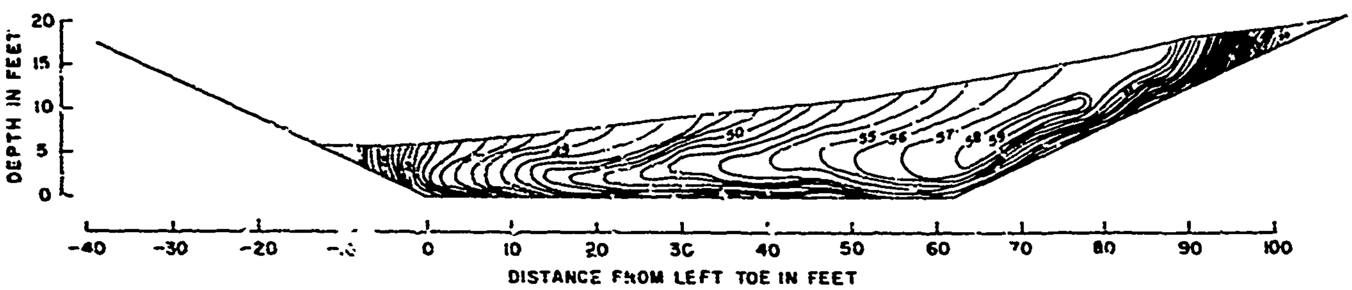
PLATE 15



B.C. STA 18+37.57

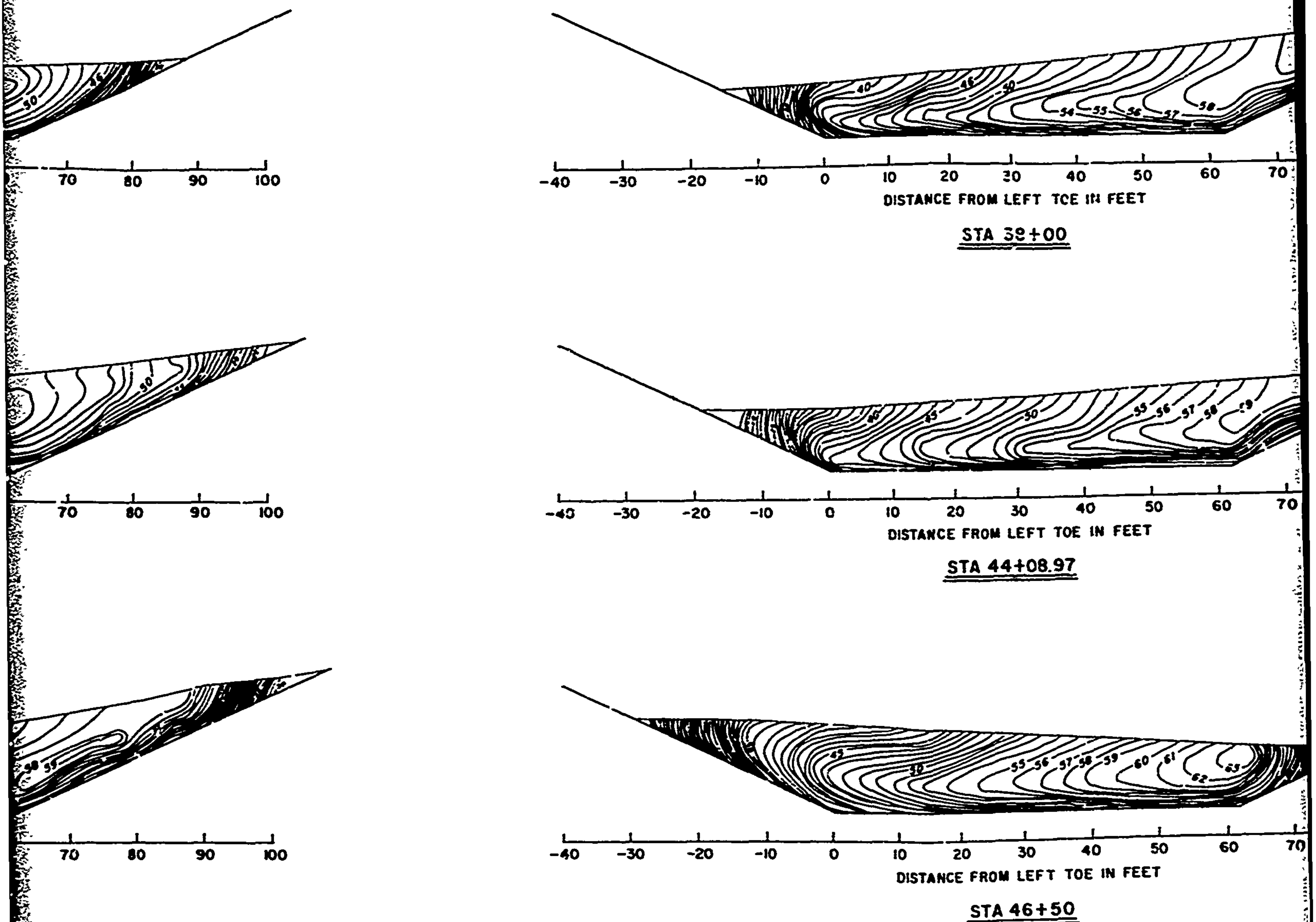


STA 22+50



STA 33+00

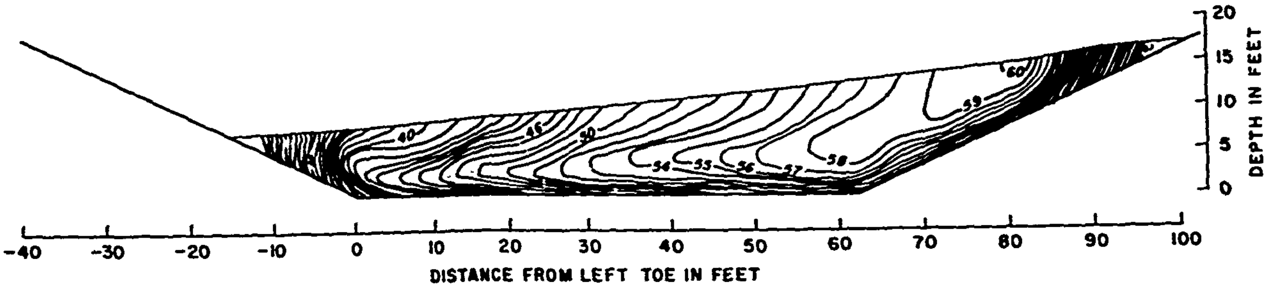
NOTE:
ALL SECTIONS SHOWN LOOKING DOWNSTREAM.
VELOCITIES ARE IN FEET PER SECOND.



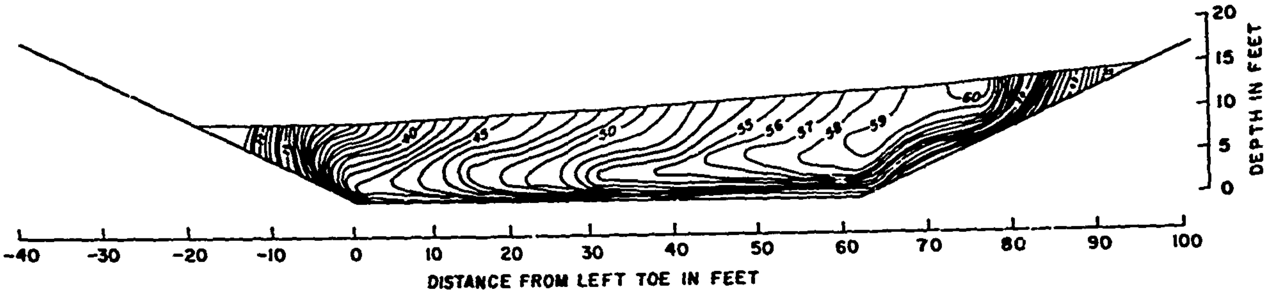
DISTANCE FROM LEFT TOE IN FEET
STA 38+00
DISTANCE FROM LEFT TOE IN FEET
STA 44+08.97
DISTANCE FROM LEFT TOE IN FEET
STA 46+50

VEL

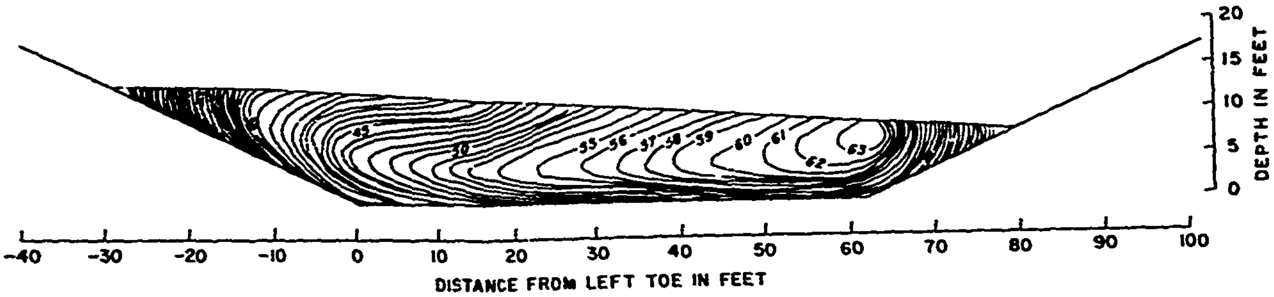
D



STA 38+00



STA 44+08.37



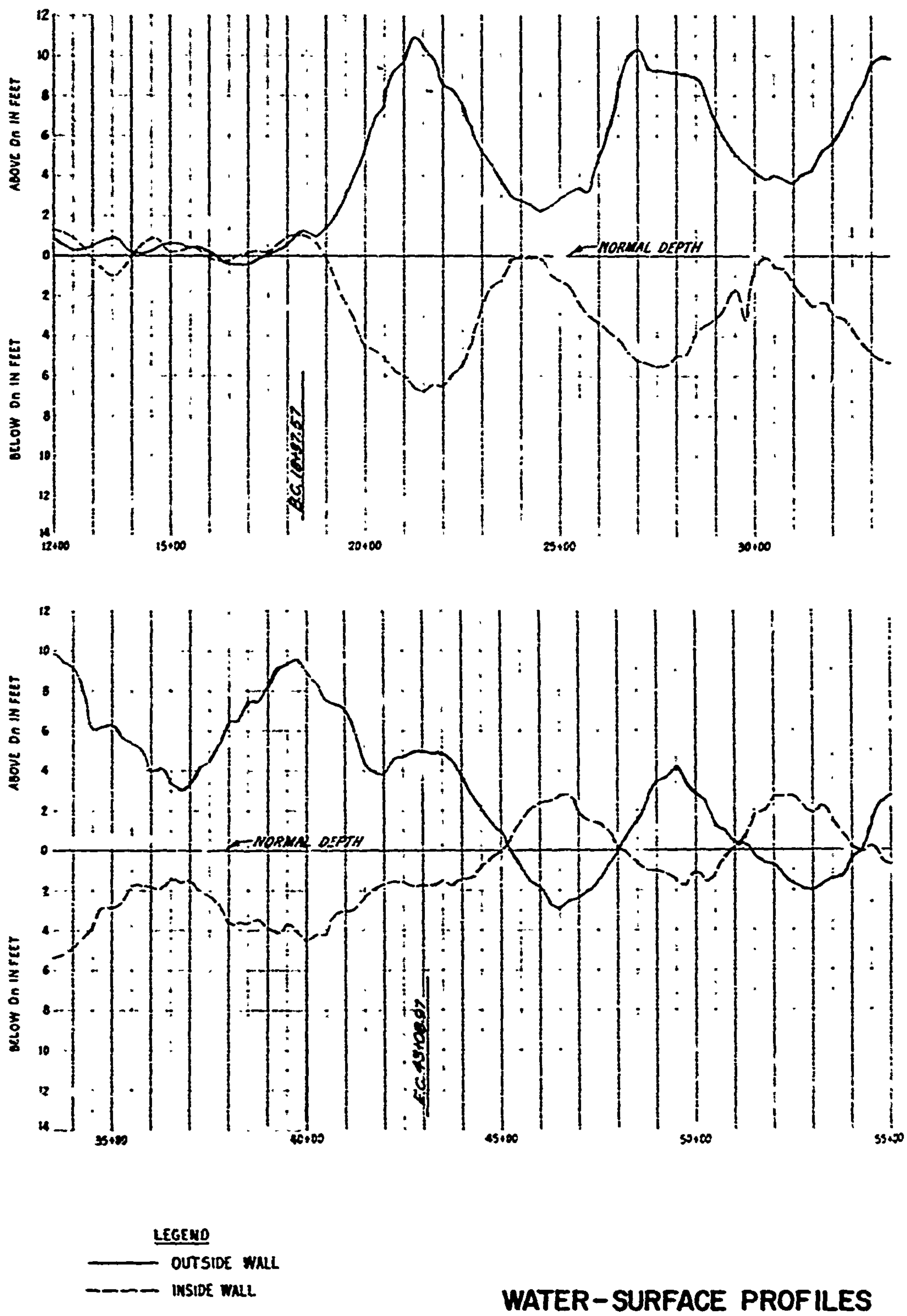
STA 46+50

VELOCITY DISTRIBUTION

TEST NO. 14

DISCHARGE 45,000 CFS
R = 885 FT
S = 0.01575

PLATE 16



WATER-SURFACE PROFILES

TEST NO. 14

DISCHARGE 45,000 CFS

PLATE 17

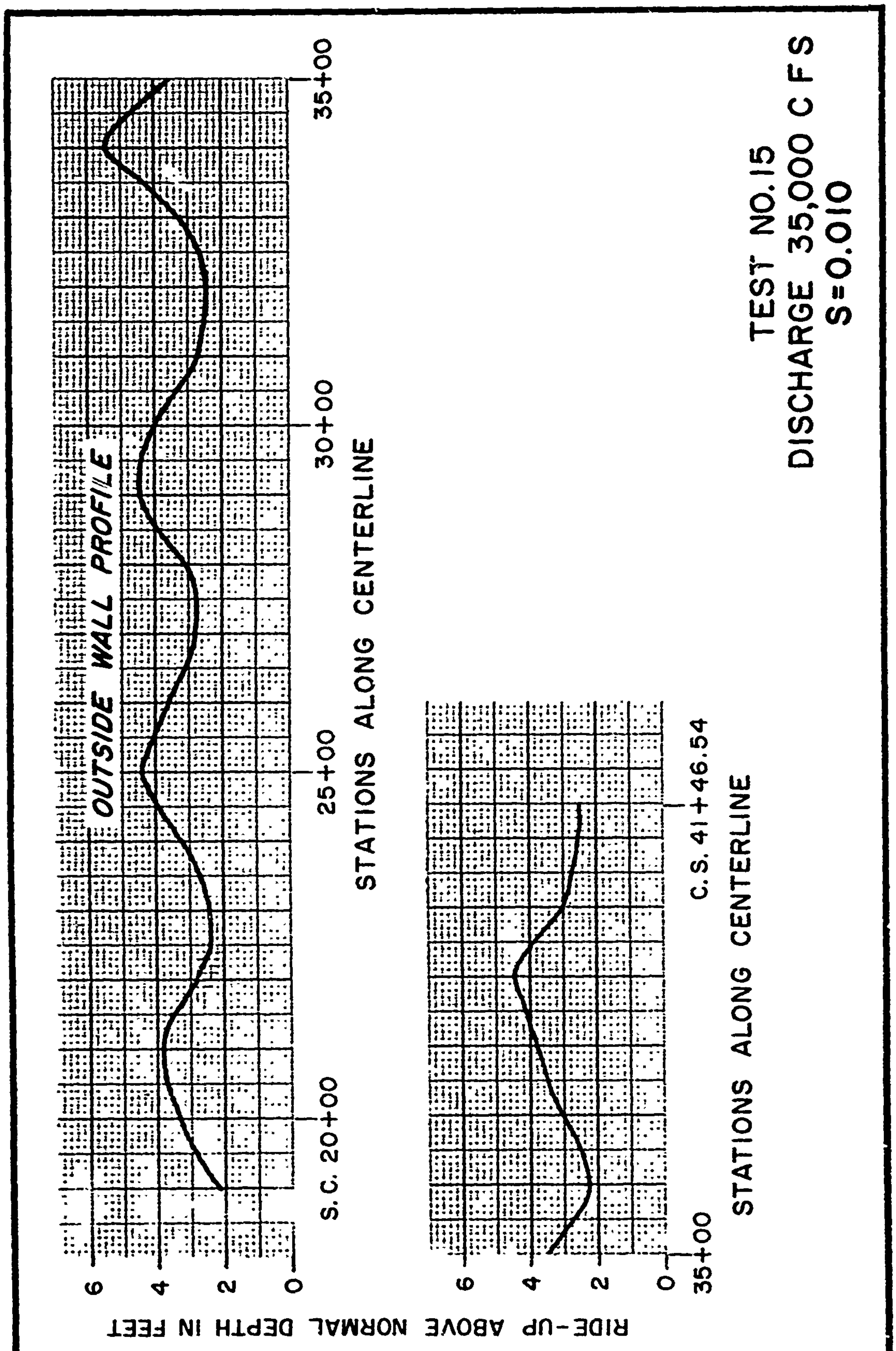
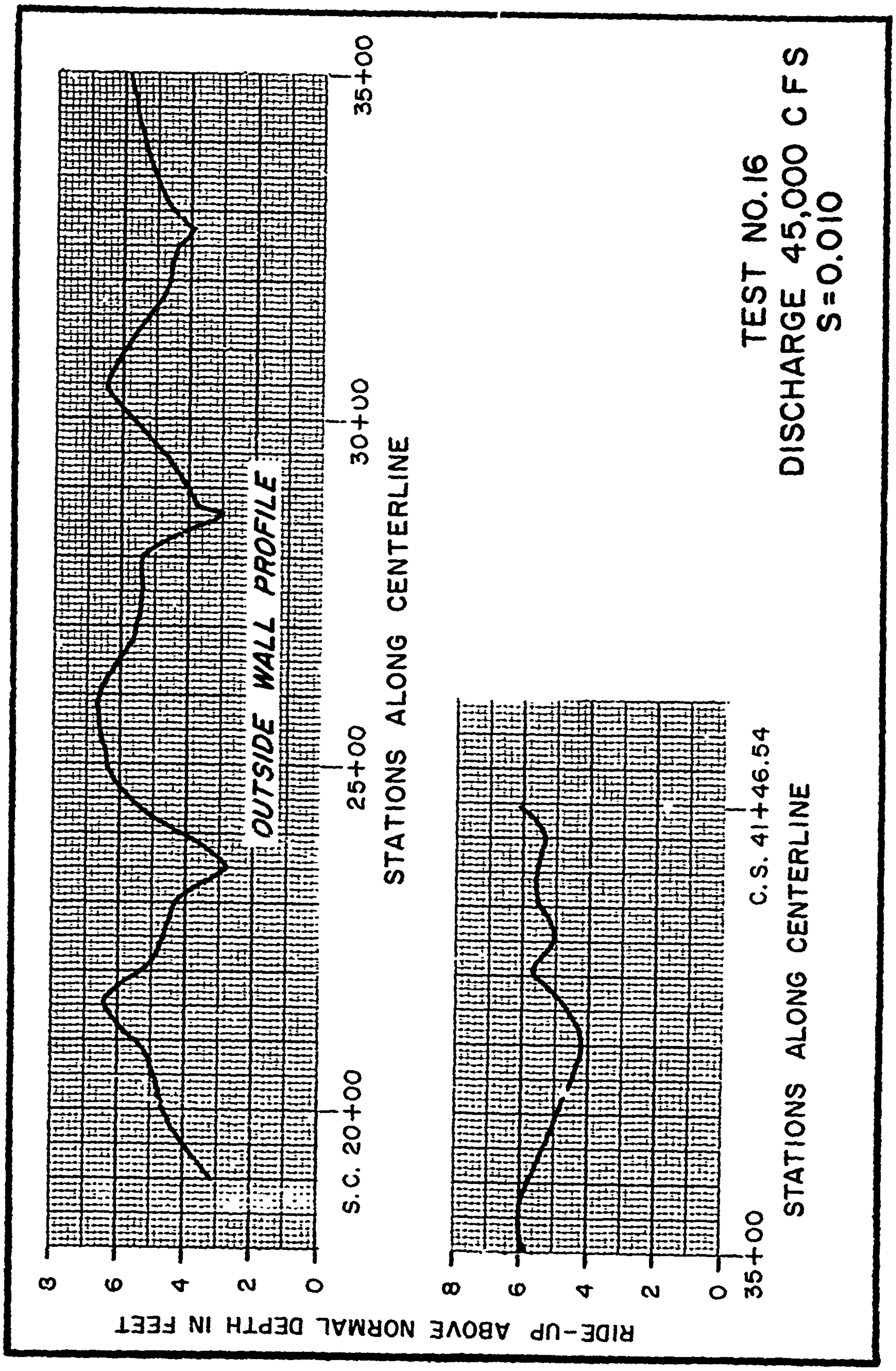
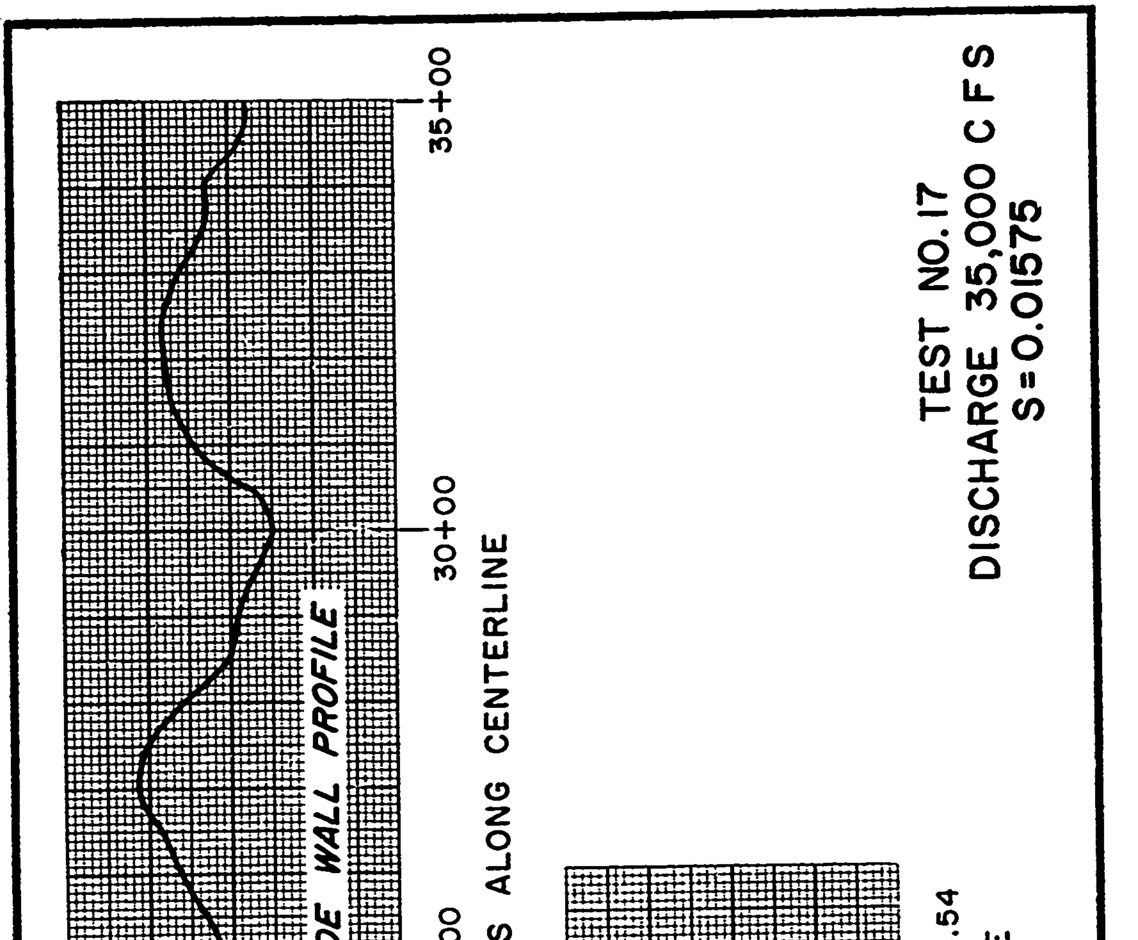

OUTSIDE WALL PROFILE
RIDE-UP ABOVE NORMAL DEPTH IN FEET
0
2
4
6
S.C. 20+00
25+00
30+00
35+00
STATIONS ALONG CENTERLINE
35+00
C.S. 41+46.54
STATIONS ALONG CENTERLINE
TEST NO.15
DISCHARGE 35,000 C F S
S=0.010

PLATE 18



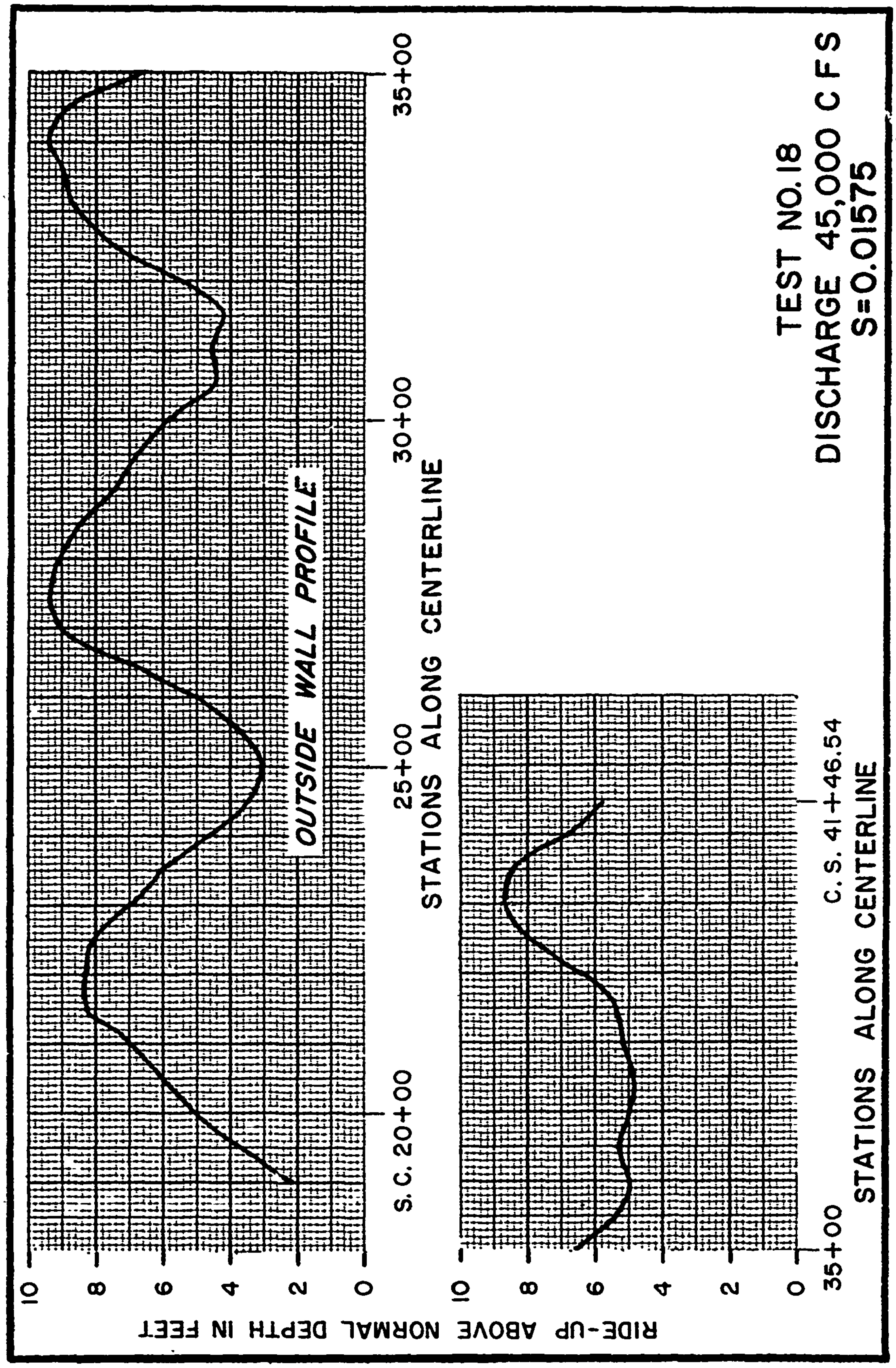
OUTSIDE WALL PROFILE
S.C. 20+00
25+00
30+00
35+00
STATIONS ALONG CENTERLINE
35+00
C.S. 41+46.54
STATIONS ALONG CENTERLINE
RIDE-UP ABOVE NORMAL DEPTH IN FEET
8
6
4
2
0
TEST NO. 16
DISCHARGE 45,000 C F S
S=0.010

PLATE 19



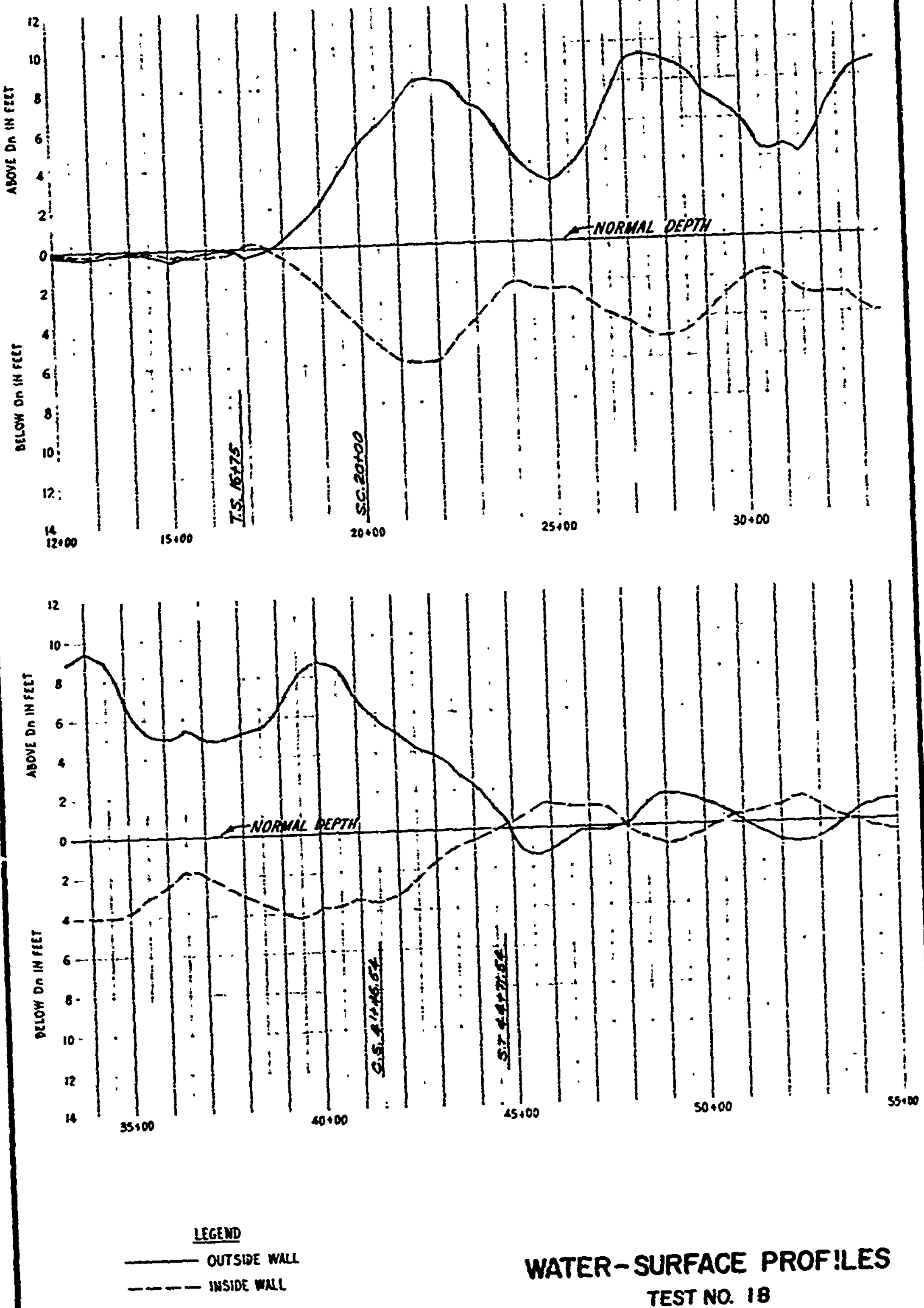
RIDE-UP ABOVE NORMAL DEPTH IN FEET
OUTSIDE WALL PROFILE
S. C. 20+00
25+00
30+00
35+00
STATIONS ALONG CENTERLINE
35+00
C. S. 41+46.54
STATIONS ALONG CENTERLINE
0
2
4
6
8
TEST NO. 17
DISCHARGE 35,000 C F S
S=0.01575

PLATE 20



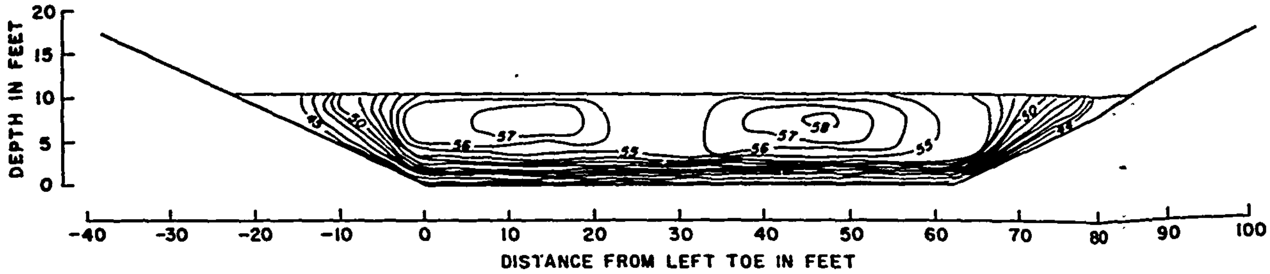
TEST NO. 18
DISCHARGE 45,000 C F S
S=0.01575
OUTSIDE WALL PROFILE
RIDE-UP ABOVE NORMAL DEPTH IN FEET
10
8
6
4
2
0
S.C. 20+00
25+00
30+00
35+00
STATIONS ALONG CENTERLINE
10
8
6
4
2
0
35+00
C. S. 41+46.54
STATIONS ALONG CENTERLINE

PLATE 21

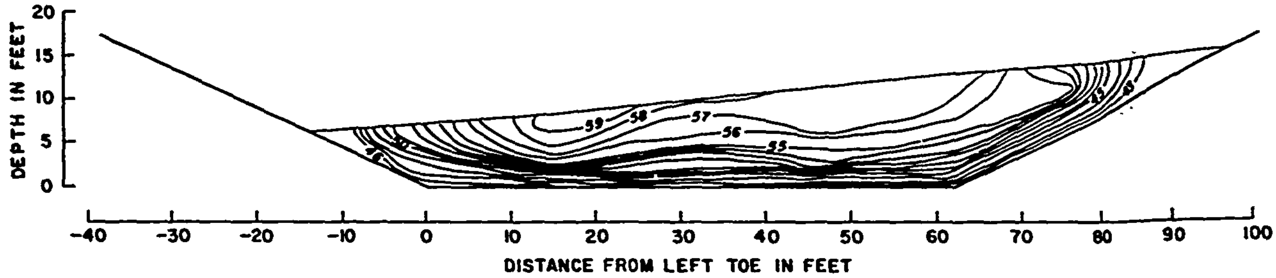


WATER-SURFACE PROFILES
TEST NO. 18
DISCHARGE 46,000 CFS

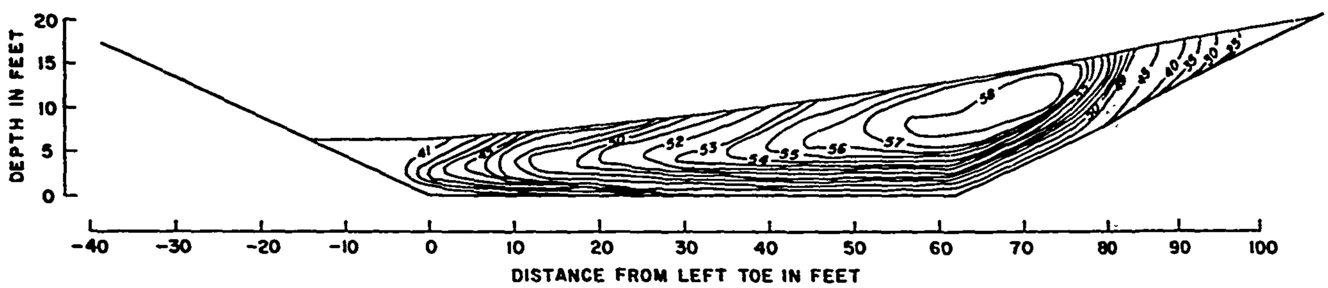
PLATE 22



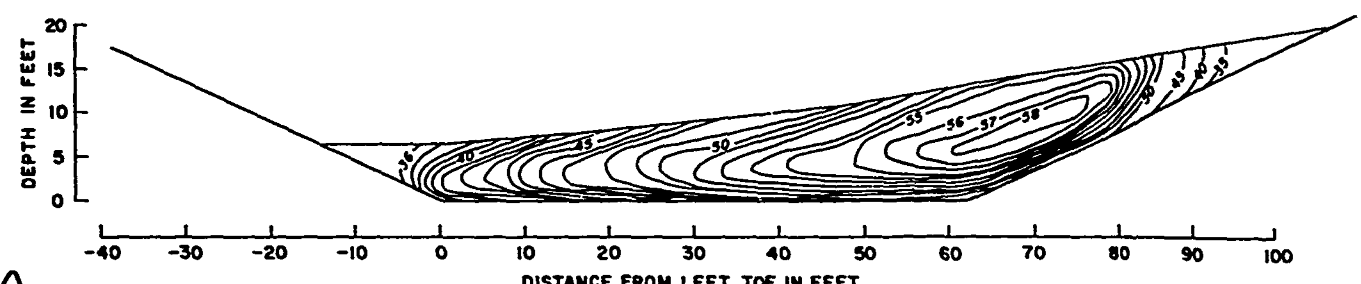
T.S. STA 16+75



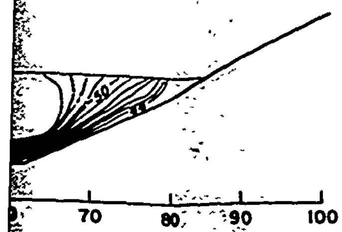
S.C. STA 20+00

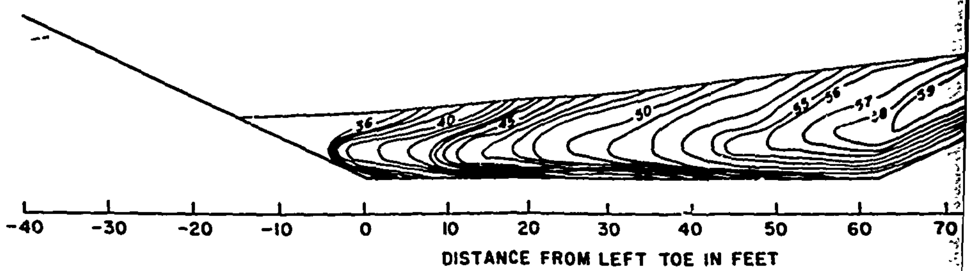


STA 27+00

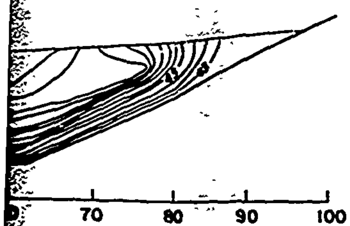


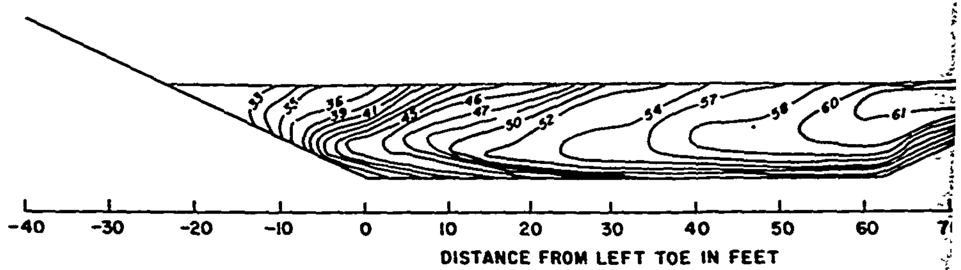
STA 34+00



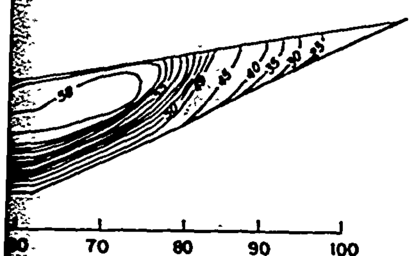


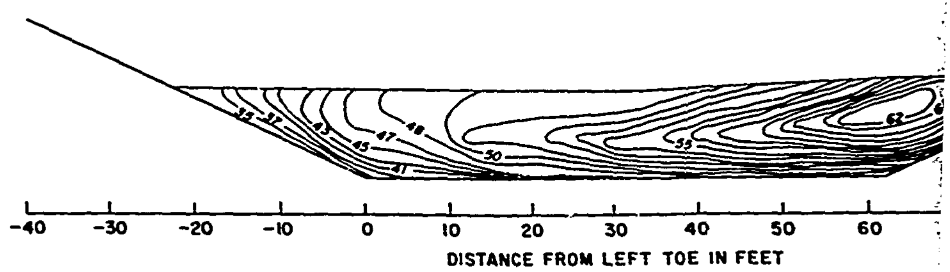
C.S. STA 41+46.54



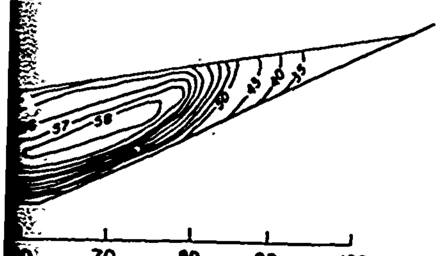


S.T. STA 44+71.54





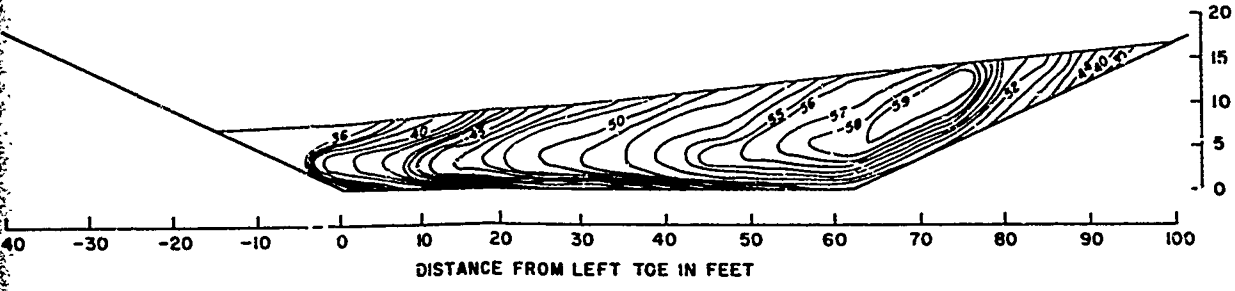
STA 50+00



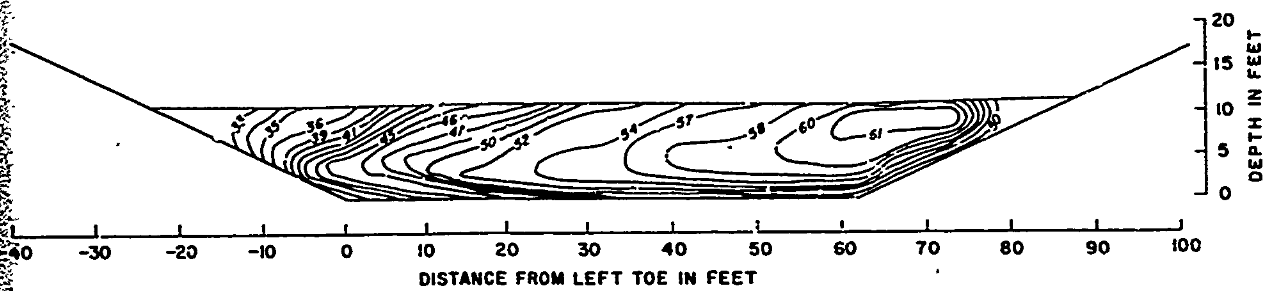
NOTE:
ALL SECTIONS SHOWN LOOKING DOWNSTREAM.
VELOCITIES ARE IN FEET PER SECOND.

VE

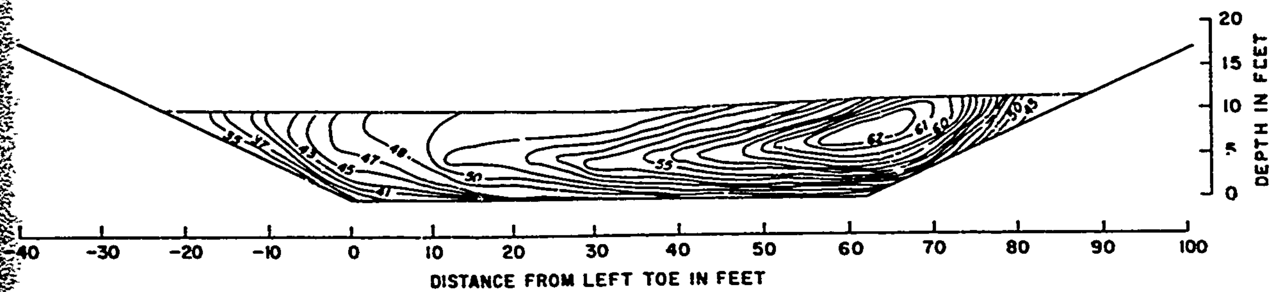
B



C.S. STA 41+46.54



S.T. STA 44+71.54



STA 50+00

NOTE.
ALL SECTIONS SHOWN LOOKING DOWNSTREAM.
VELOCITIES ARE IN FEET PER SECOND.

VELOCITY DISTRIBUTION

TEST NO. 18

DISCHARGE 45,000 C F S
R = 885 FT
S = 0.01575

PLATE 23

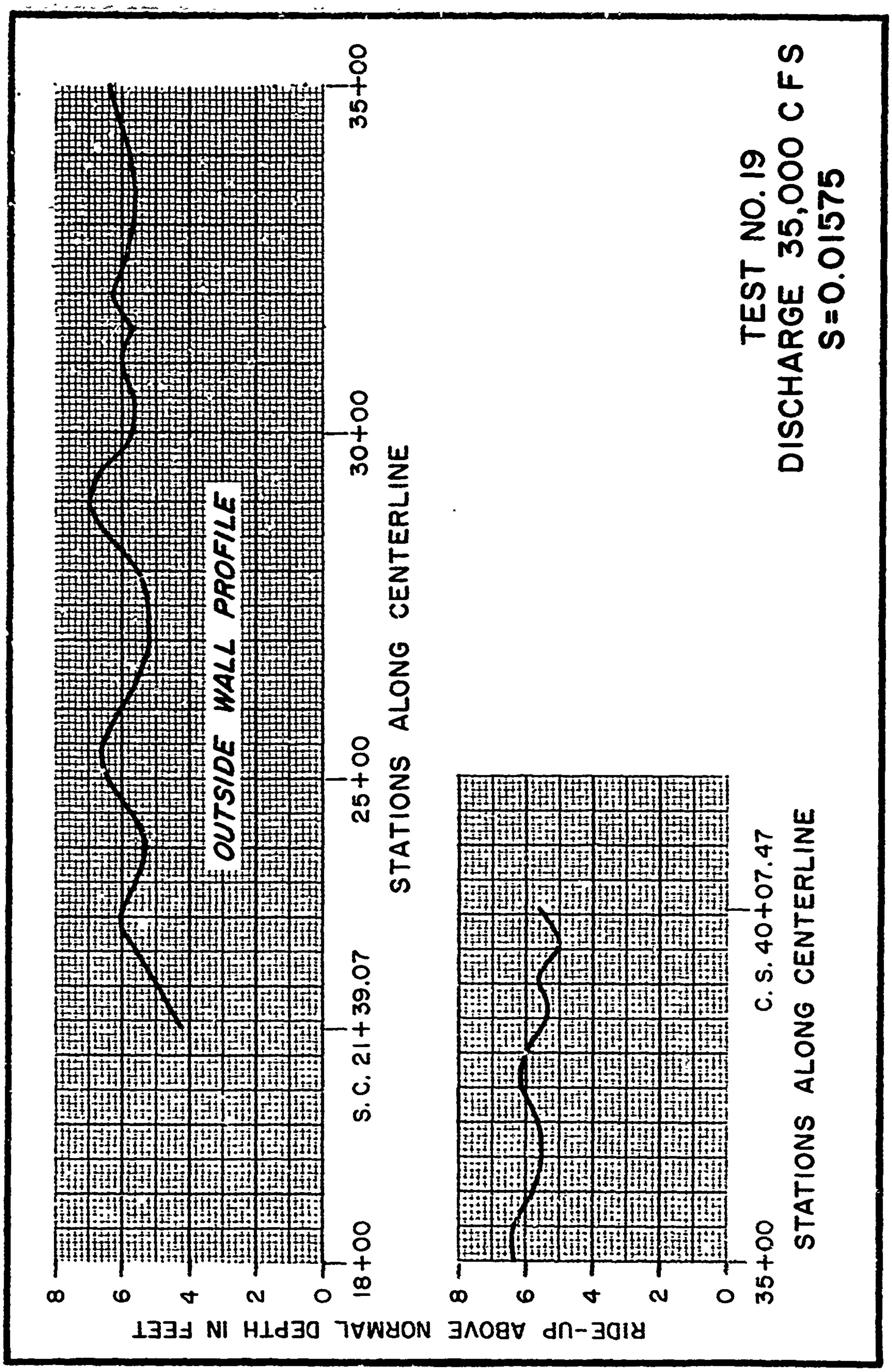
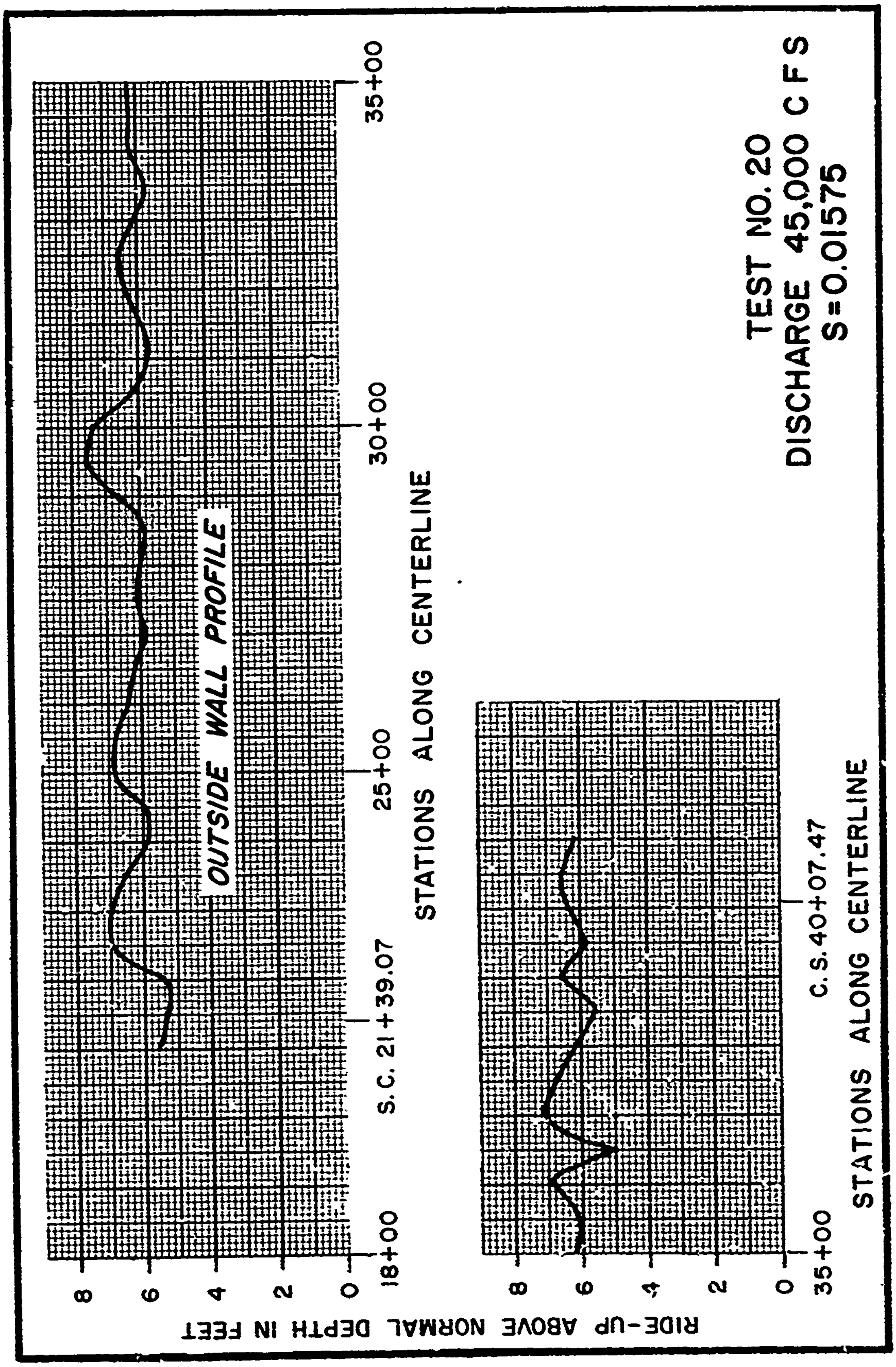
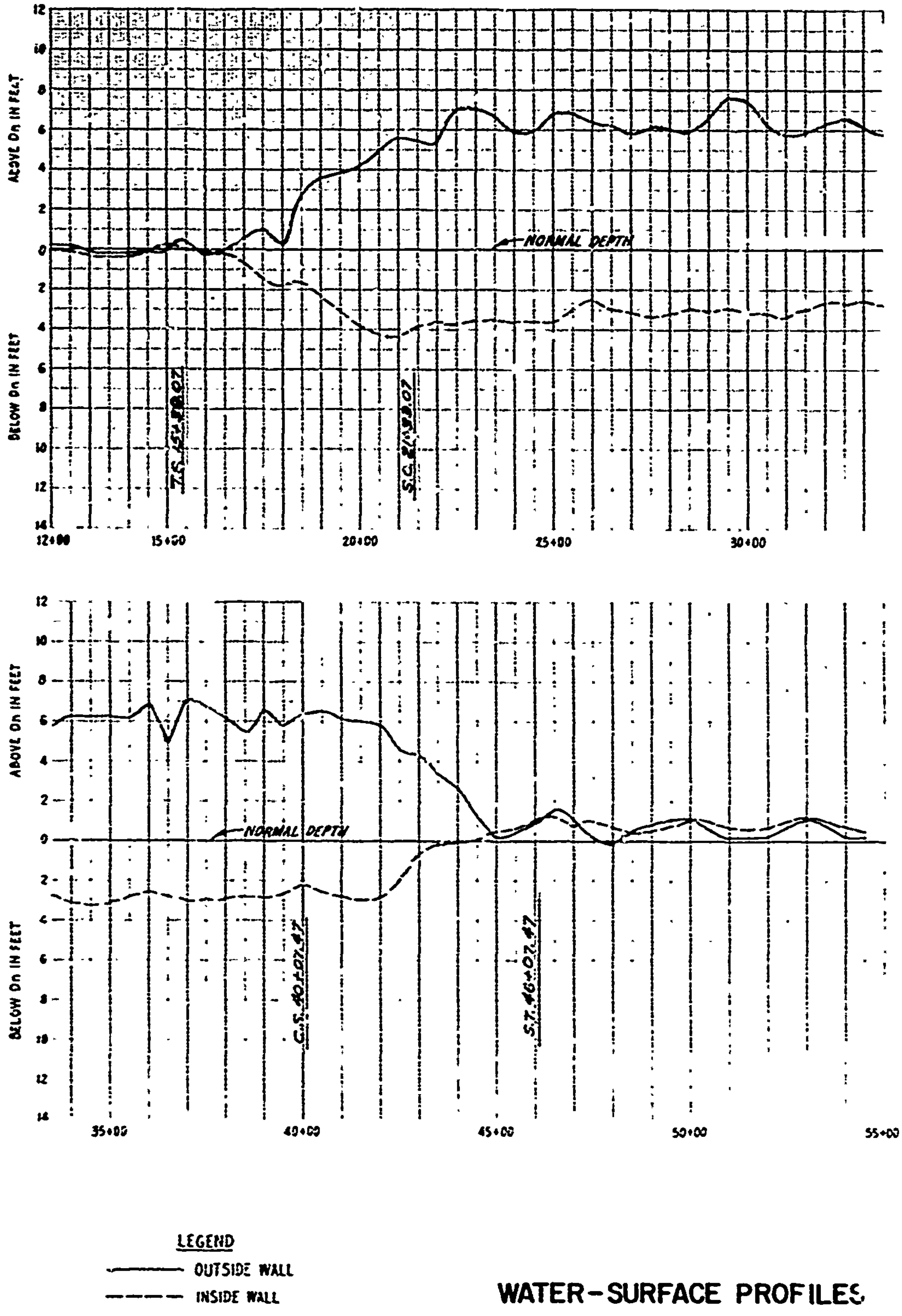

OUTSIDE WALL PROFILE
RIDE-UP ABOVE NORMAL DEPTH IN FEET
0
2
4
6
8
18+00
S. C. 21+39.07
25+00
30+00
35+00
STATIONS ALONG CENTERLINE
35+00
C. S. 40+07.47
STATIONS ALONG CENTERLINE
TEST NO. 19
DISCHARGE 35,000 C F S
S=0.01575

PLATE 24



TEST NO. 20
DISCHARGE 45,000 C F S
S=0.01575
OUTSIDE WALL PROFILE
STATIONS ALONG CENTERLINE
STATIONS ALONG CENTERLINE
RIDE-UP ABOVE NORMAL DEPTH IN FEET
18+00
S.C. 21+39.07
25+00
30+00
35+00
35+00
C.S. 40+07.47
0
2
4
6
8

PLATE 25

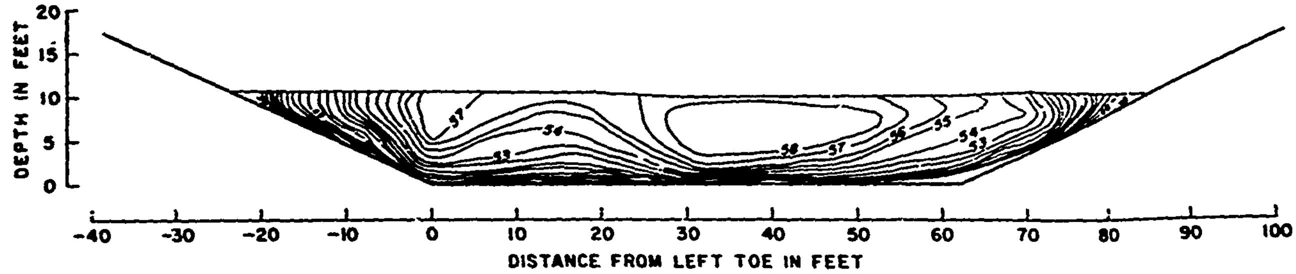


WATER-SURFACE PROFILES

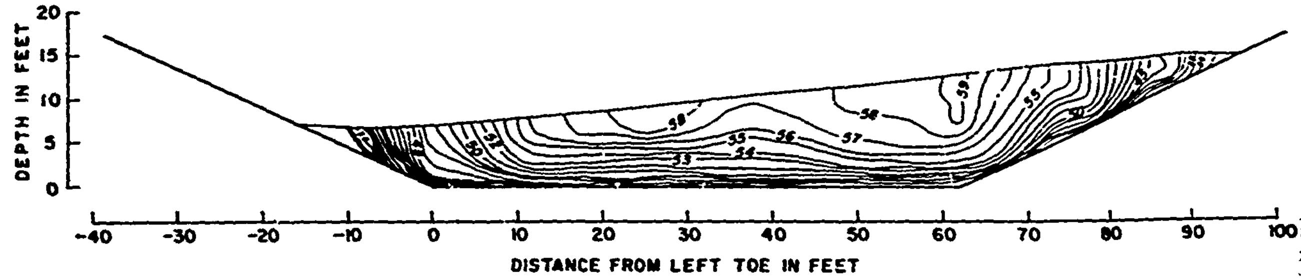
TEST NO. 20

DISCHARGE 45,000 CFS

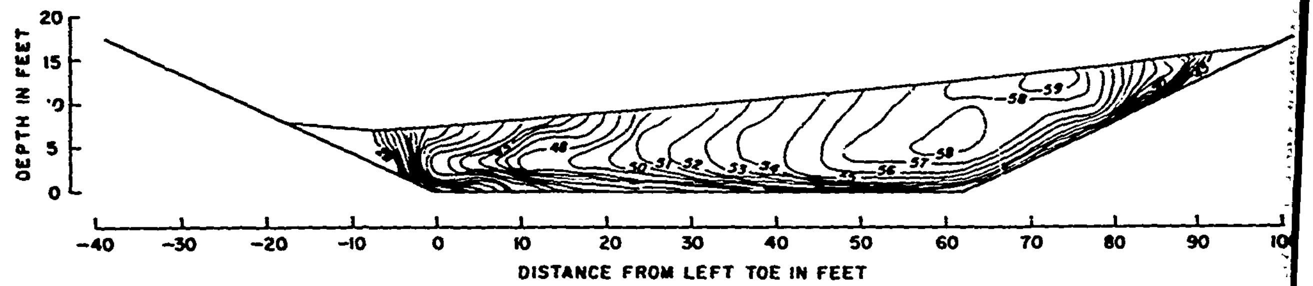
PLATE 26



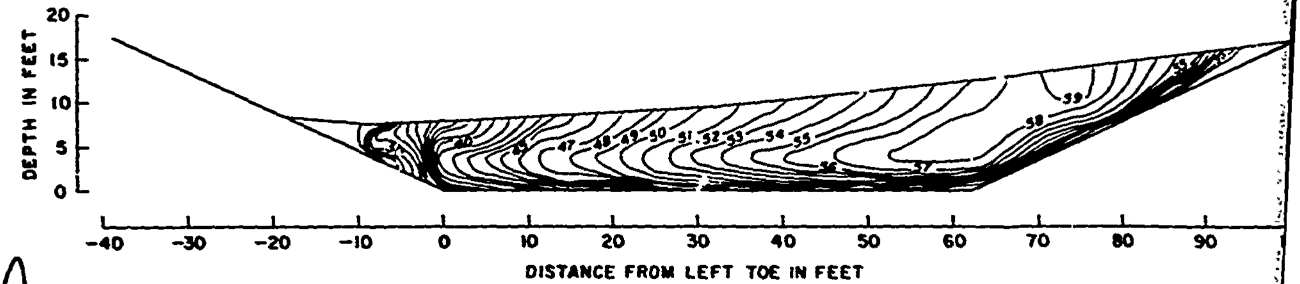
T.S. STA 15+39.07



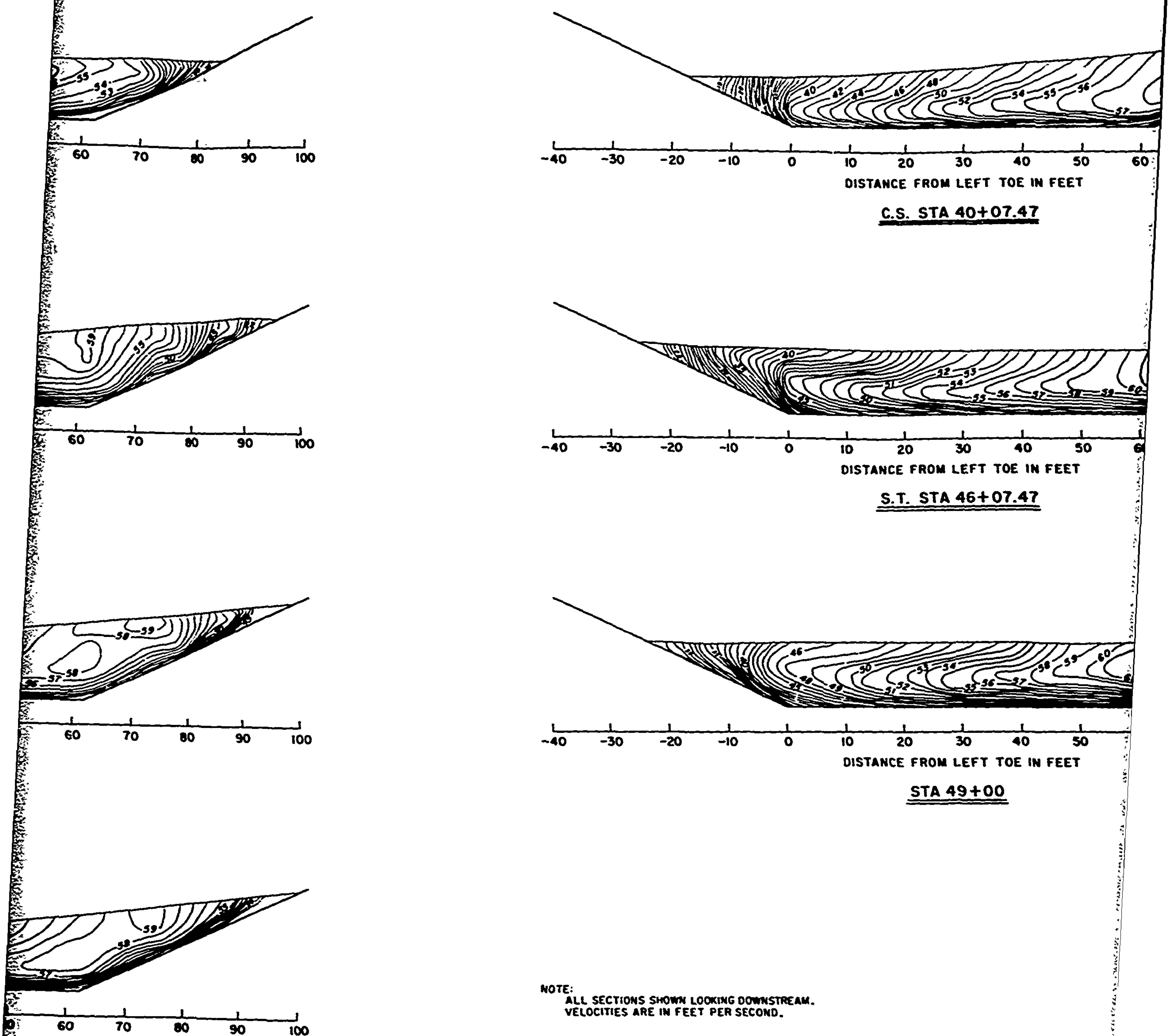
S.C. STA 21+39.07



STA 27+50

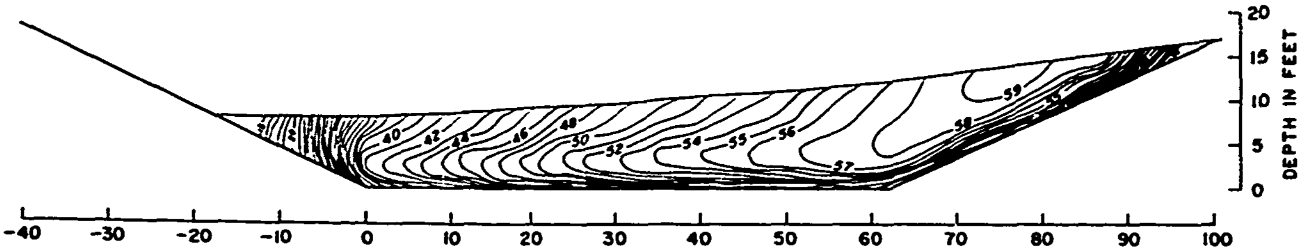


STA 33+00

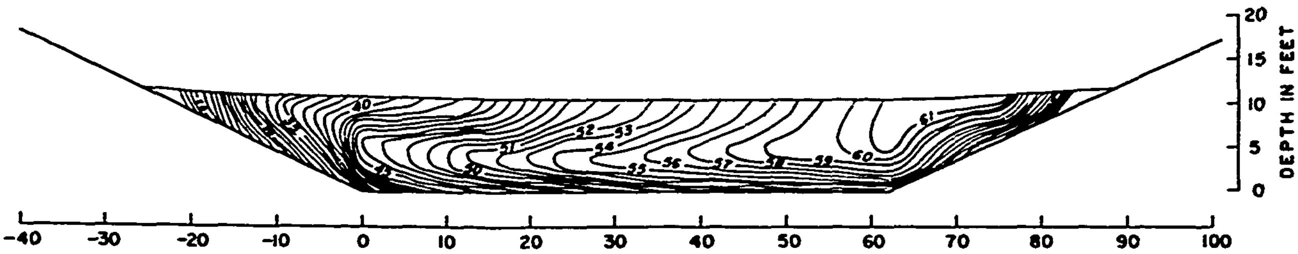


NOTE:
ALL SECTIONS SHOWN LOOKING DOWNSTREAM.
VELOCITIES ARE IN FEET PER SECOND.

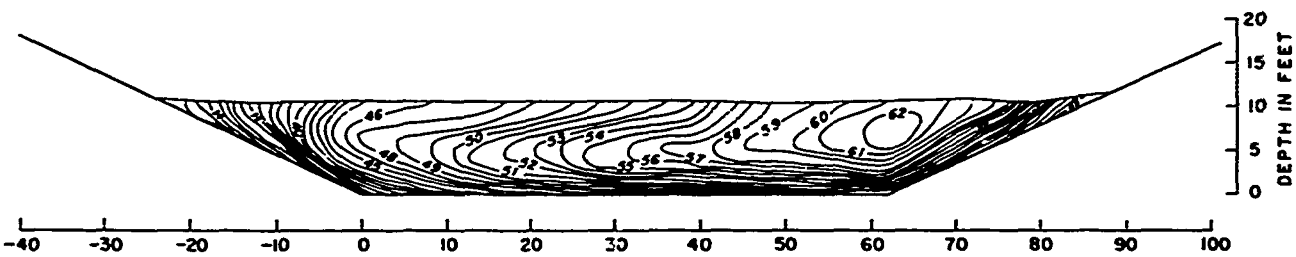
B



C.S. STA 40+07.47



S.T. STA 46+07.47



STA 49+00

NOTE:
ALL SECTIONS SHOWN LOOKING DOWNSTREAM.
VELOCITIES ARE IN FEET PER SECOND.

VELOCITY DISTRIBUTION

TEST NO. 20

DISCHARGE 45,000 C F S
R = 885 FT
S = 0.01575

PLATE 27

APPENDIX A: A STUDY OF SUPERCRITICAL FLOW IN A CURVED CIRCULAR CONDUIT

INTRODUCTION

1. The Los Angeles County drainage basin is made up of many steep and narrow canyons. The slopes of these canyons vary from 3 to 15 percent. Recent hillside developments and fires have created a dangerous, debris-laden flood potential. The floods of past years have caused great damage to homes and people. Existing and future developments will need adequate protection from these floods. With the limited amount of available rights-of-way and the extremely restricted working space, the circular conduit, which is just as economical as cast-in-place covered section, is most desirable in these highly developed residential canyon areas. However, the lack of available hydraulic data on circular conduits with high-velocity flow prompted a model investigation to determine the flow characteristics in the curved conduit.

2. This report presents the results of two model designs, designated tests 1 and 2, on supercritical flow in a curved circular conduit. The study plan was to utilize a lucite model that would simulate actual flow conditions within the hydraulic design range for reinforced concrete pipe. The two model designs were on an 8 percent slope and a 90-deg bend. Test 1 had a 90-ft-radius curve without spirals and test 2 had a 150-ft-radius curve with 24-ft spirals at each end of the simple curve.

MODEL

3. The models, constructed to an undistorted scale ratio of 1:10, simulated an 8-ft-diam conduit. Test 1 reproduced about 400 ft of conduit proper, which was cut into simulated 4-ft prototype sections. Test 2 reproduced about 310 ft of conduit, which was cut into simulated 6-ft prototype sections (see plates A1 and A6). Each section was bonded together with epoxy glue.

4. The entire conduit, including the rectangular channel approach and the circular exit channel, was molded of transparent lucite pipe that

permitted direct observation of flow. The assembled lucite pipe was supported by a series of wooden "A" frames set on concrete pads. Wooden cradles were set between the pipe and the "A" frames, which were adjustable in elevation to provide a model slope of 8 percent. A 16,000-gal forebay elevated 4 ft above the ground was used to provide the required energy head. The forebay was equipped with baffles to ensure tranquil flow conditions. A control gate, downstream of the forebay, was used to obtain the required depth at the upstream end of the approach channel.

5. The following accepted equations of hydraulic similitude were used to express the mathematical relations between the dimensions and hydraulic quantities of the model and the prototype.

Dimension	Ratio	Scale Relation
Length	L_r	1:10
Area	$A_r = L_r^2$	1:100
Velocity	$V_r = L_r^{1/2}$	1:3.162
Discharge	$Q_r = L_r^{5/2}$	1:316.20
Roughness coe[illegible]ent	$N_r = L_r^{1/6}$	1:1.468

6. Measurements of [illegible]rge, depths, pressures, and velocity of flow can be transferred quan[illegible]tively from model to prototype equivalents by means of the above scale relations.

TEST PROCEDURE

7. The study program was made up of two designs (tests 1 and 2). Each test consisted of three runs or discharges, namely, 1740, 1900, and 2060 cfs (see tabulation below). For each run, a depth of 0.8 diameter was obtained at the upstream end of the model by means of a control gate.

Run	Discharge cfs	Upstream Velocity, fps	d_n ft	d_c ft
1	1740	45	4.34	7.96
2	1900	48	4.56	7.98
3	2060	50	4.81	7.99

8. Two Prandtl pitot tubes were used to measure velocities. The approach velocity was measured upstream of the curve in the rectangular section. The other Prandtl pitot tube was located in the downstream section; at this location the soffit of the conduit was notched to provide access to the flow. The recording positions of the Prandtl pitot tube were on the centerline-quarter points. The velocity data were classified as random samplings and only served as an overall check on the flow mechanics and for a prorated average velocity at the control station. Velocity measurements were taken for each test run; however, they are not shown in this report.

9. Water-surface readings for each test run were taken by visual observation of the inside and outside waterlines. A transparent, movable, wraparound gage was used for the measurements; the gage scale was marked in percent of the diameter.

10. The pressure data were obtained by using piezometers. Numerous piezometer openings, located at critical points in the conduit, were connected to glass manometers by flexible tubing and provided means of obtaining pressure data throughout the model.

TEST 1, WITHOUT SPIRAL

11. Test 1 consisted of an 8-ft-diam conduit alined with tangents and simple curve on a centerline radius of 90 ft and a longitudinal slope of 0.08. The total deflection angle was $89^{\circ}07'36''$ with a curve length of 140 ft. The lengths of tangents preceding and following the curve were 71.60 and 94.00 ft, respectively (plate A1). Piezometer locations around the conduit are shown in plate A2.

12. Test results are summarized by the data plotted in plates A3 and A4. They show the transverse water-surface profiles and pressure graphs at sections 4 and 8 for the different discharges. Water surface was difficult to define because of the extreme turbulence, the aeration, and the swirling flow. Swirling flow, defined as the clockwise spiral flow returning to the inner side of the conduit, was observed at several

locations. Plate A5 presents views of the flow conditions for the different discharges.

TEST 2, WITH SPIRAL

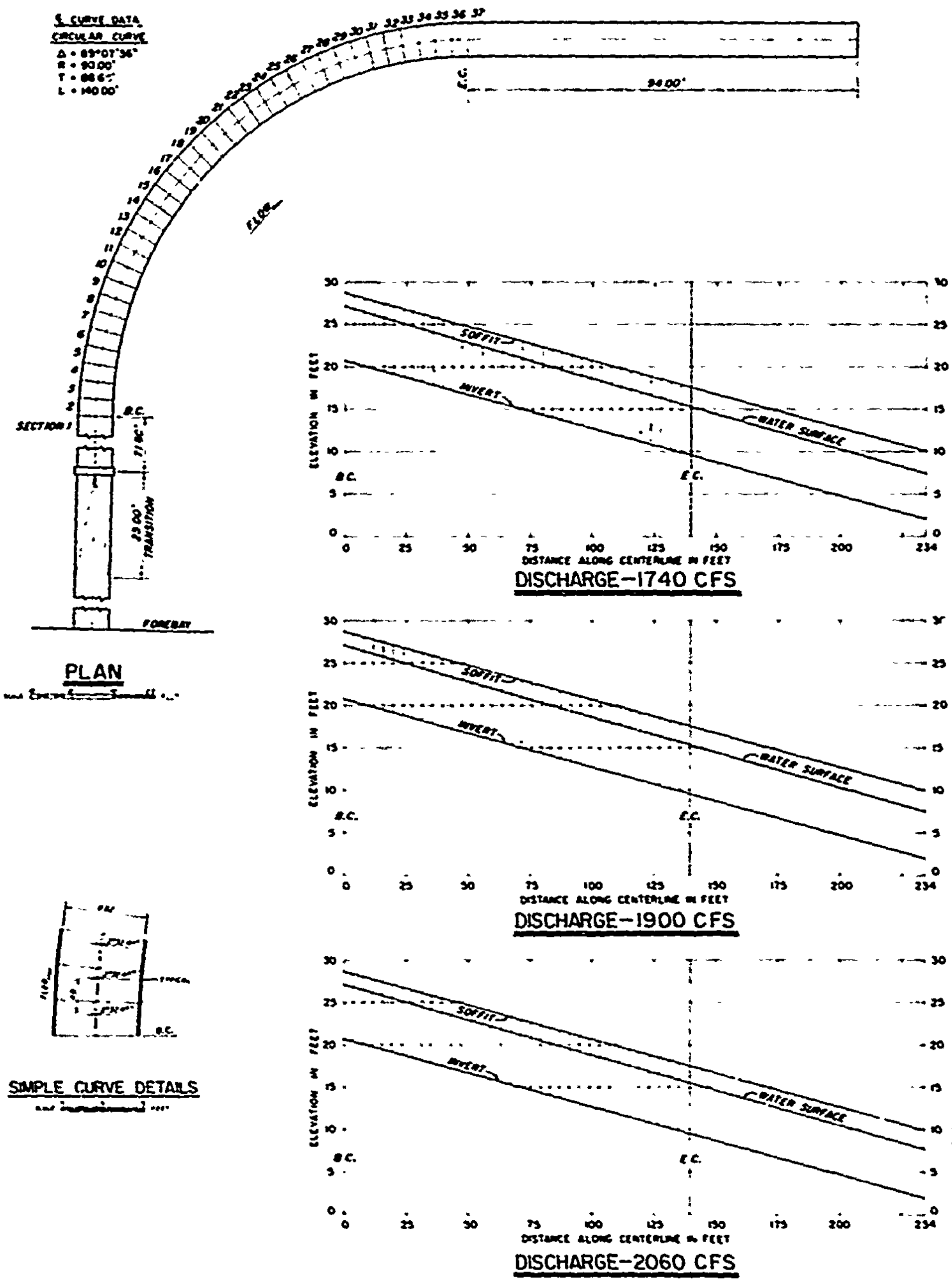
13. Test 2 was alined with spirals at each end of the simple curve with a centerline radius of 150 ft. The lengths of the spirals were 24 ft and the length of the curve was 211.17 ft. The total deflection angle was 90°00'00", including an 80°39'36" central angle of the simple curve. The tangent lengths upstream and downstream of the spiral curves were 71.60 and 67.50 ft, respectively. The spiral length of 24 ft was chosen because use of 4-, 6-, and 8-ft lengths of reinforced-concrete pipe sections is common practice. It should be mentioned that this spiral is not the modified spiral used on rectangular and trapezoidal channels, but a modified ten-chord spiral (plate A6).

14. With the added spirals, the model was again tested with the same three discharges used in test 1. The results of the tests indicated that flow conditions in the spiral and the curve were somewhat improved. Plates A7 and A8 show a plot of the actual transverse water-surface profiles and pressure graphs at sections 4 and 8 for the different discharges. The longitudinal water-surface profiles are shown in plate A9. Plate A10 presents views of the different flow conditions.

CONCLUSIONS

15. The simple curve geometries for tests 1 and 2 are not comparable. The improved flow conditions observed in test 2 (plates 6, 8, and 10) over those in test 1 (plates 3, 4, and 5) probably result from the increased curve radius (150 ft, test 2; 90 ft, test 1) rather than from the use of spiral transitions.

16. Tests on comparable circular conduit curves with and without spiral transitions and for various curve radii, conduit diameters, and Froude numbers are needed to establish firm design criteria.



NOTE.

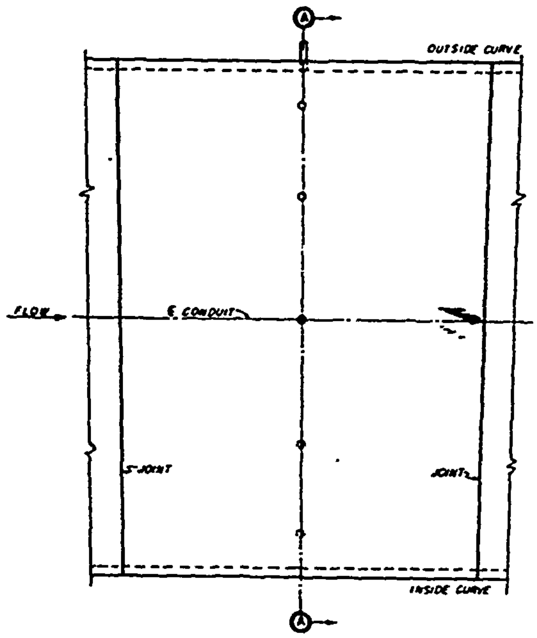
WATER SURFACE SHOWN IS THE COMPUTED EQUIVALENT STRAIGHT ALINEMENT VALUES WITH SLOPE CORRECTIONS AT 0.88-DIAMETER DEPTH.

PIEZOMETER LOCATIONS FOR EACH SECTION OF CONDUIT ARE SHOWN IN PLATE A2

SIMPLE CURVE LAYOUT AND COMPUTED WATER SURFACE

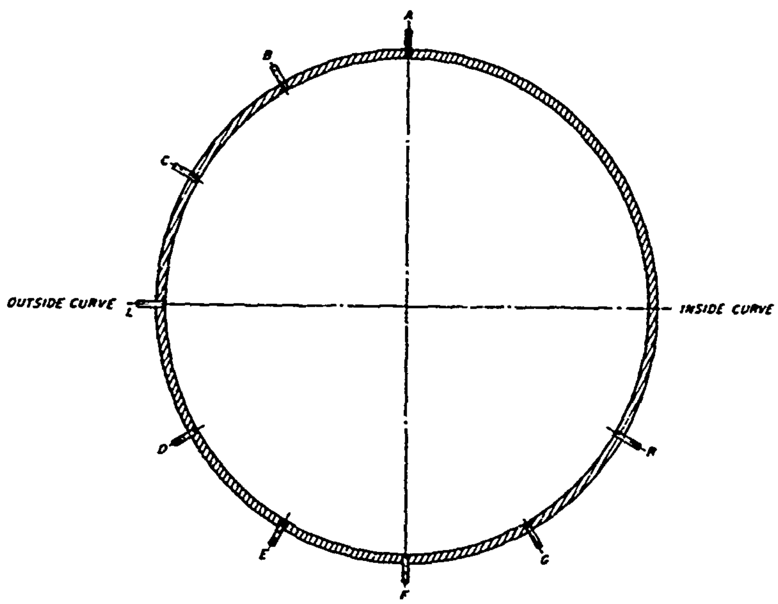
TEST 1: RUNS 1, 2, AND 3

PLATE A1



PLAN

(TYPICAL SECTION OF CONDUIT)



SECTION A-A

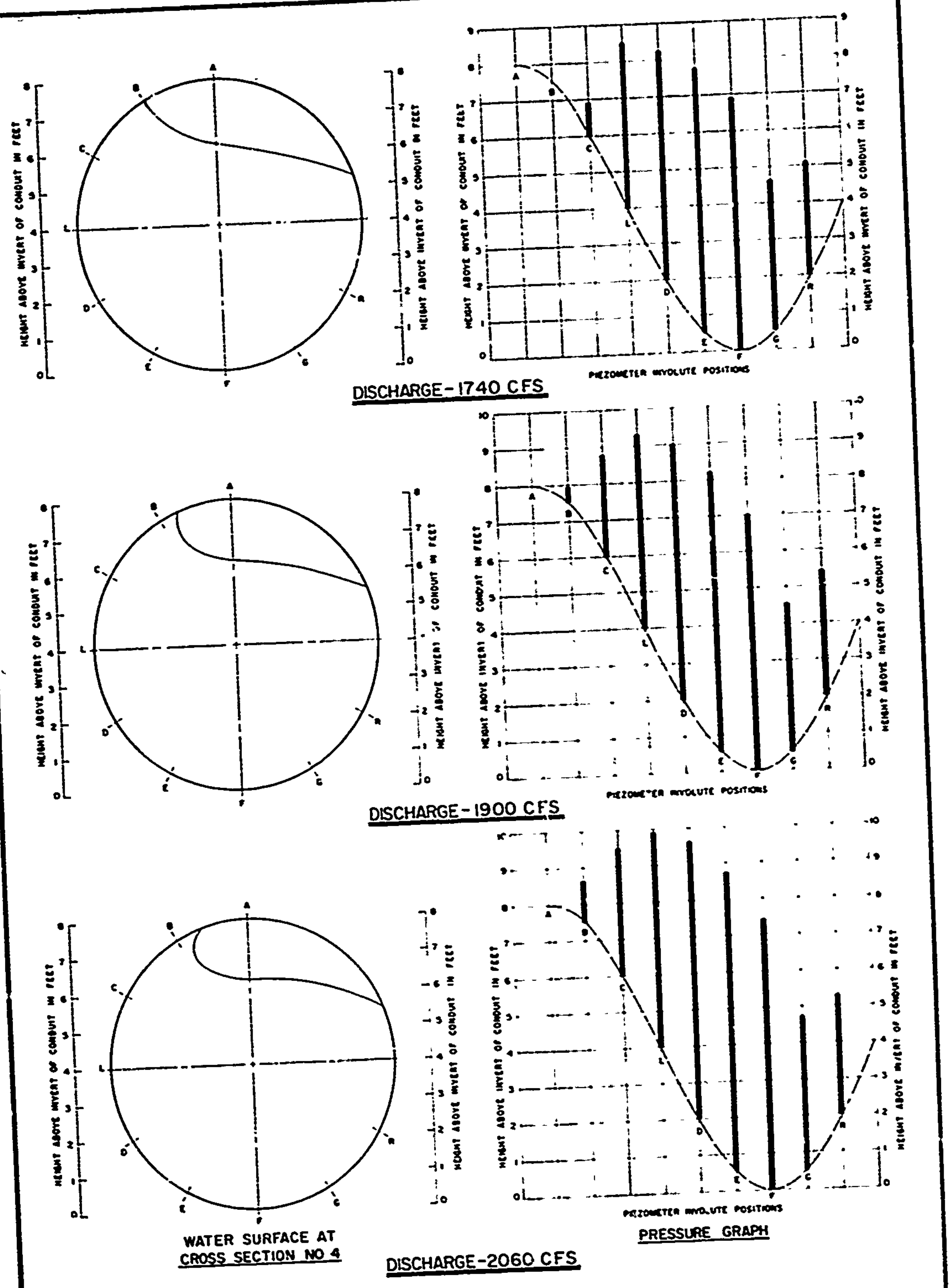
(SECTIONS 4 AND 8)

PIEZOMETER NO.	HEIGHT ABOVE INVERT	
	DIAMETER	FEET
A	1.00	8.02
B	0.93	7.48
C	0.75	6.02
L	0.50	4.01
D, R	0.25	2.00
E, G	0.07	0.54
F	0	0

PIEZOMETER LOCATIONS

SECTIONS 4 AND 8

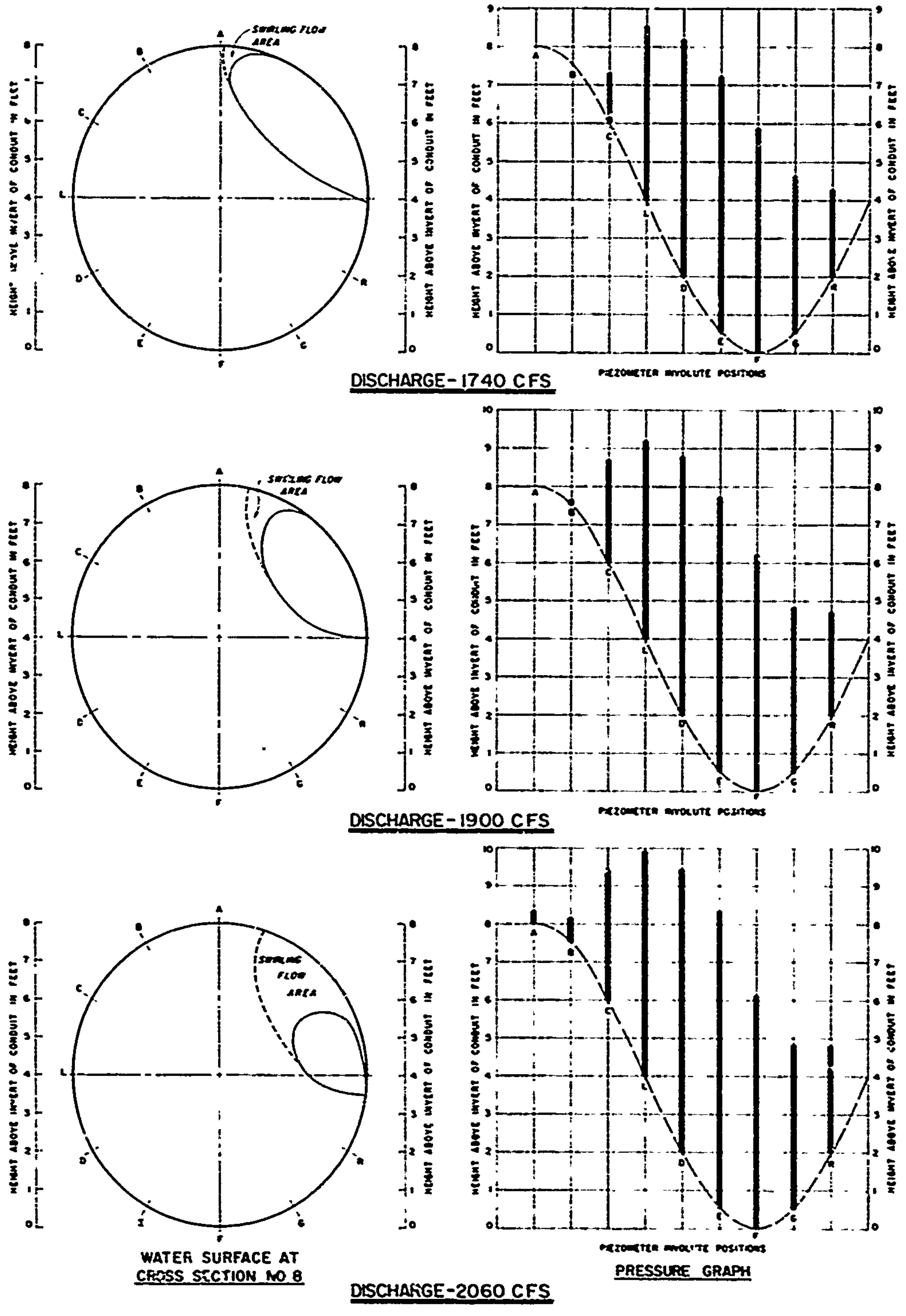
PLATE A2



NOTE
ALL CROSS SECTIONS SHOWN LOOKING DOWNSTREAM
PRESSURE BARS ARE IN FEET OF WATER.
CROSS SECTION LOCATIONS ARE SHOWN IN PLATE A1

WATER SURFACES AND PRESSURES
AT CROSS SECTION NO. 4
TEST 1 RUNS 1, 2, AND 3

PLATE A3



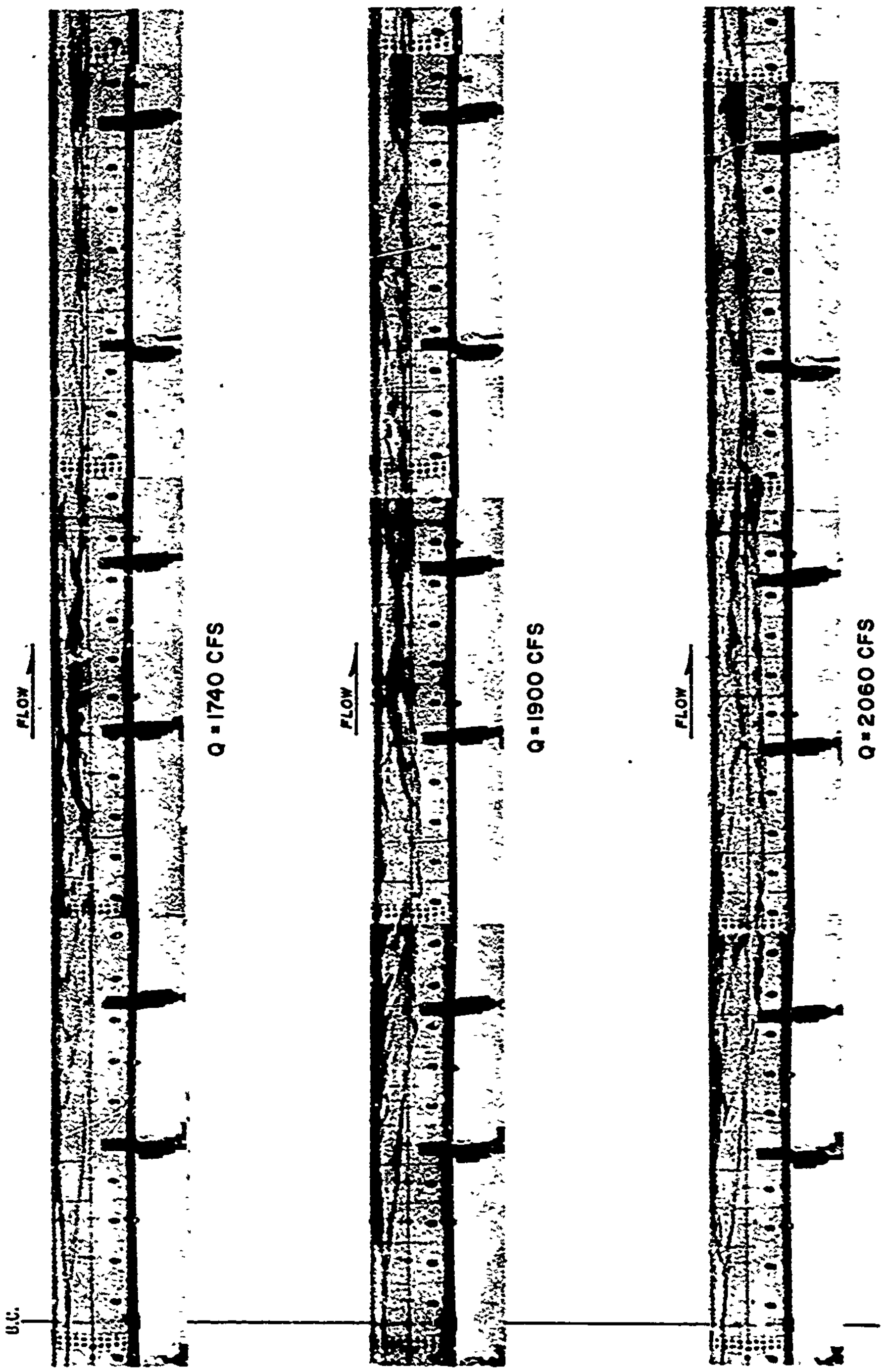
NOTE

ALL CROSS SECTIONS SHOWN LOOKING DOWNSTREAM.
PRESSURE BARS ARE IN FEET OF WATER.
CROSSSECTION LOCATIONS ARE SHOWN IN PLATE A1

WATER SURFACES AND PRESSURES AT CROSS SECTION NO. 8

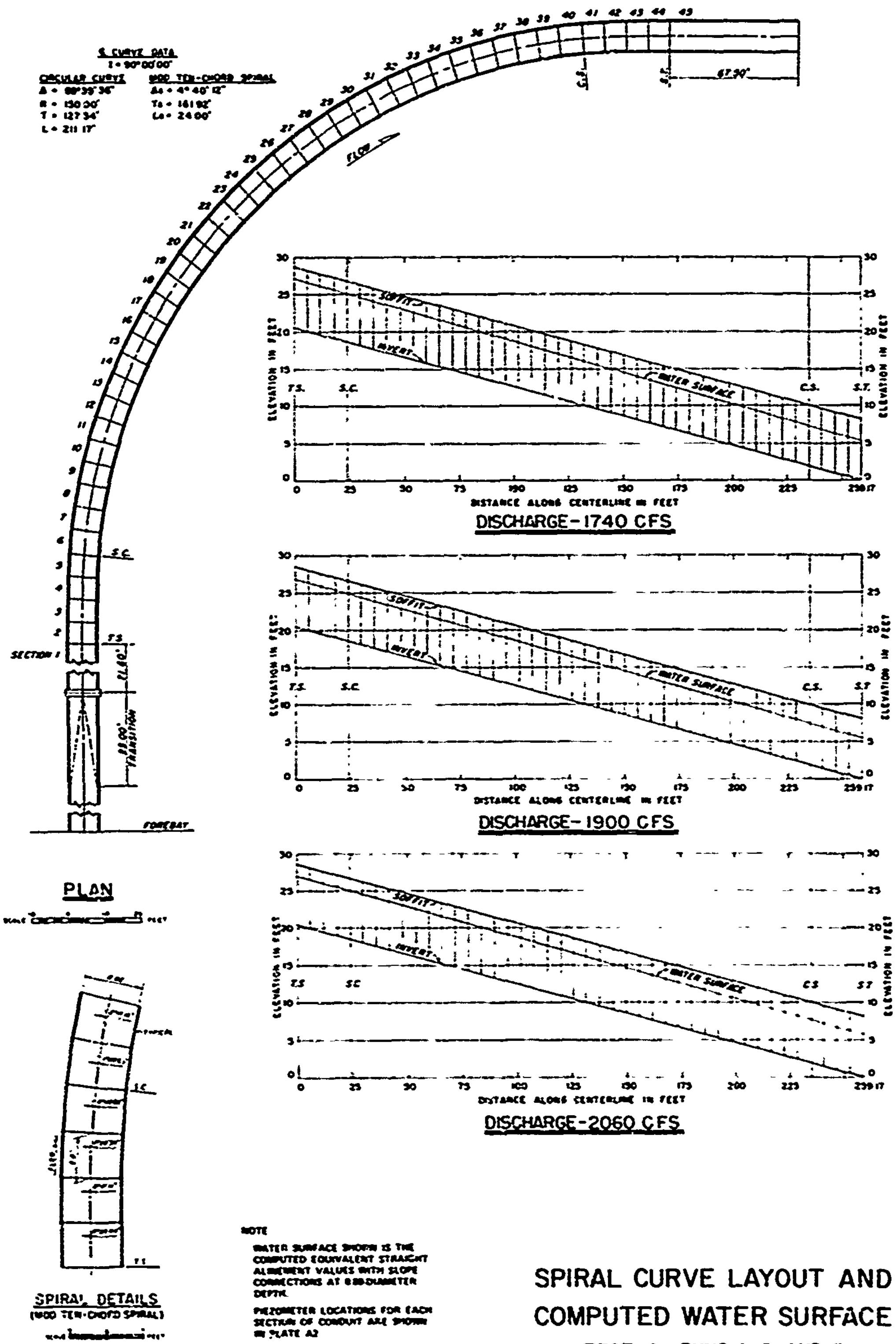
TEST I: RUNS 1, 2, AND 3

PLATE A4



TEST 1 FLOW CONDITIONS IN CONDUIT WITH SIMPLE CURVE ONLY

PLATE A5



NOTE

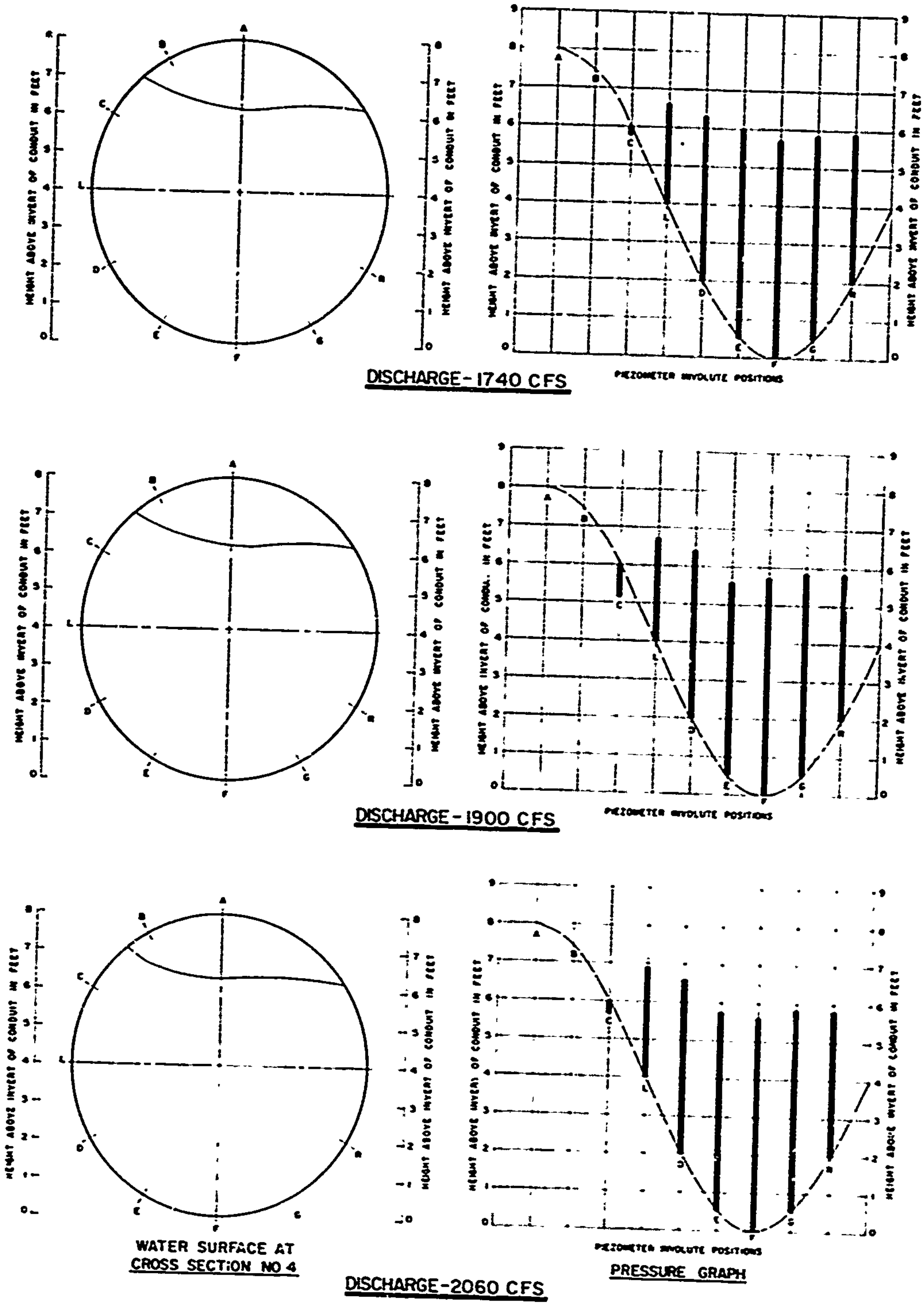
WATER SURFACE SHOWN IS THE COMPUTED EQUIVALENT STRAIGHT ALINEMENT VALUES WITH SLOPE CONNECTIONS AT 0.80-DIAMETER DEPTH.

PIEZOMETER LOCATIONS FOR EACH SECTION OF CONDUIT ARE SHOWN IN PLATE A2

SPIRAL CURVE LAYOUT AND COMPUTED WATER SURFACE

TEST 2: RUNS 1, 2, AND 3

PLATE A6



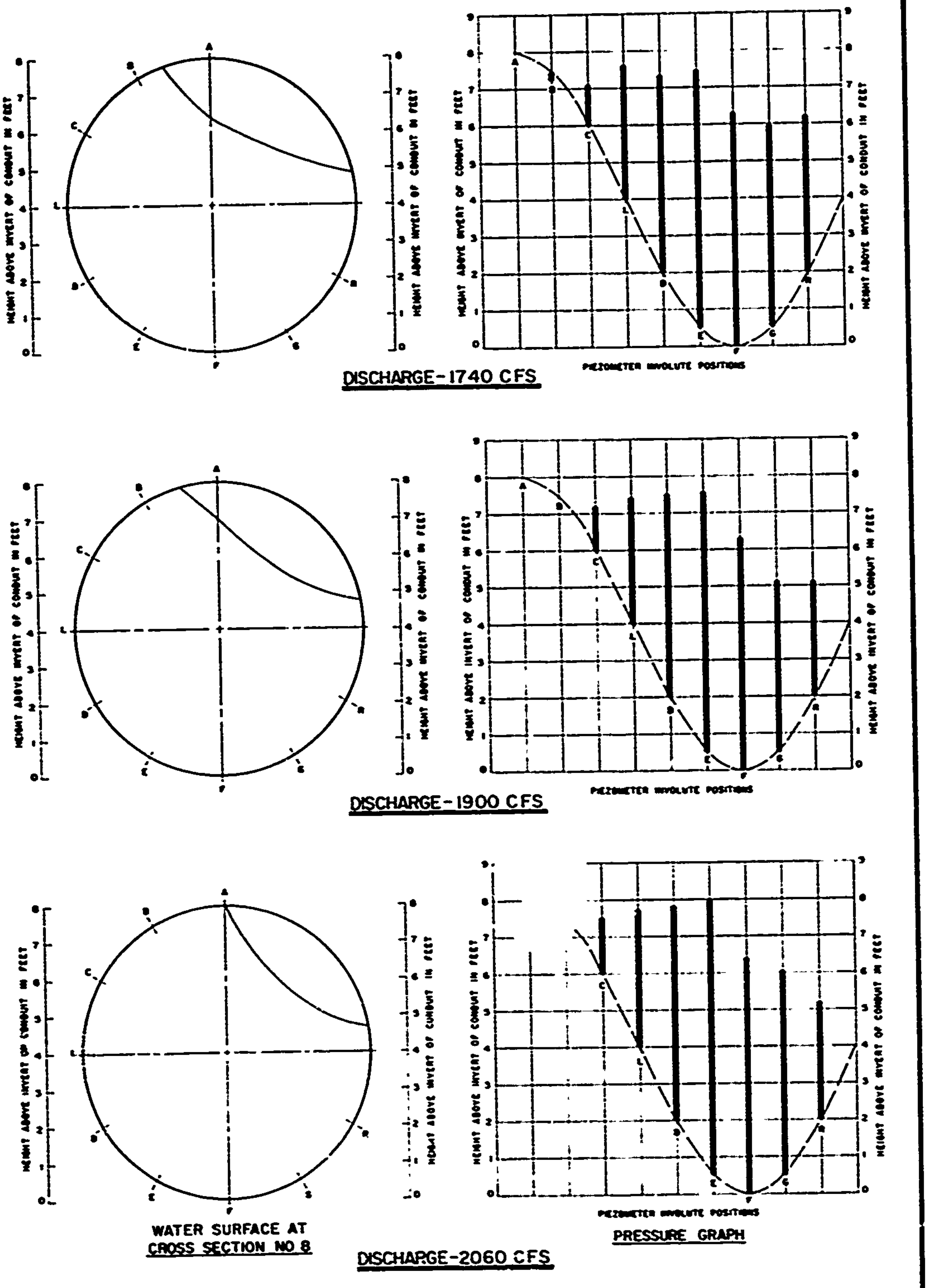
NOTE

ALL CROSS SECTIONS SHOWN LOOKING DOWNSTREAM
PRESSURE BARS ARE IN FEET OF WATER
CROSS SECTION LOCATIONS ARE SHOWN IN PLATE A6

WATER SURFACES AND PRESSURES AT CROSS SECTION NO. 4

TEST 2: RUNS 1, 2, AND 3

PLATE A7

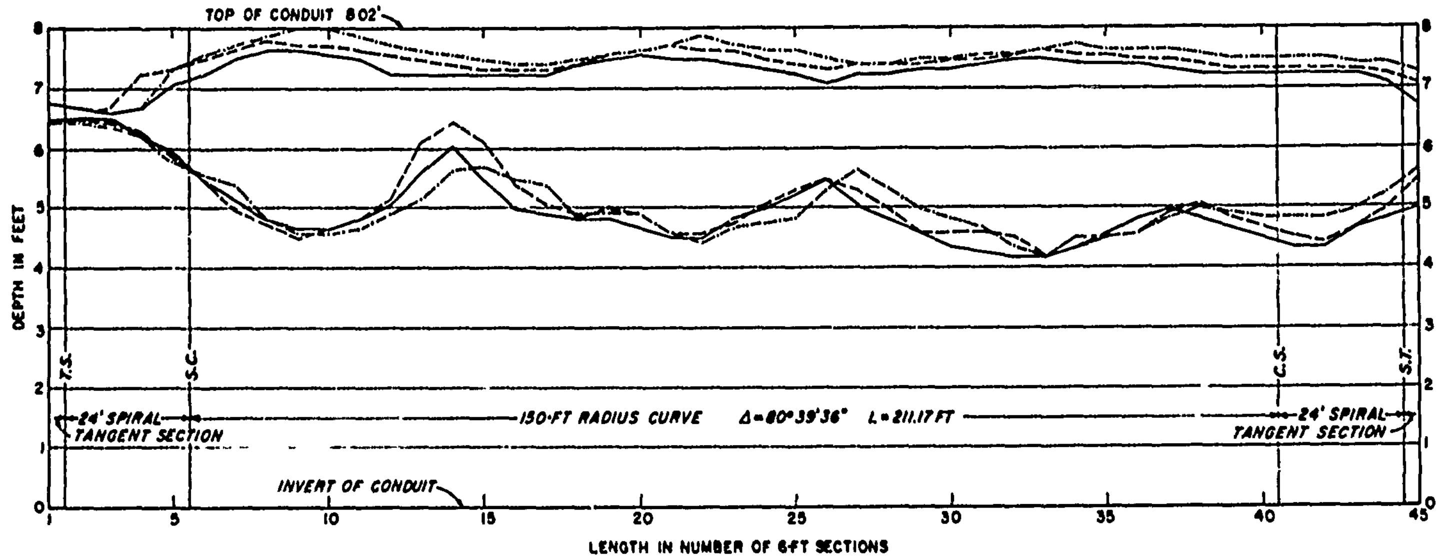


NOTE.
ALL CROSS SECTIONS SHOWN LOOKING DOWNSTREAM.
PRESSURE BARS ARE IN FEET OF WATER.
CROSS-SECTION LOCATIONS ARE SHOWN IN PLATE A6.

WATER SURFACES AND PRESSURES AT CROSS SECTION NO. 8

TEST 2: RUNS 1, 2, AND 3

PLATE A8

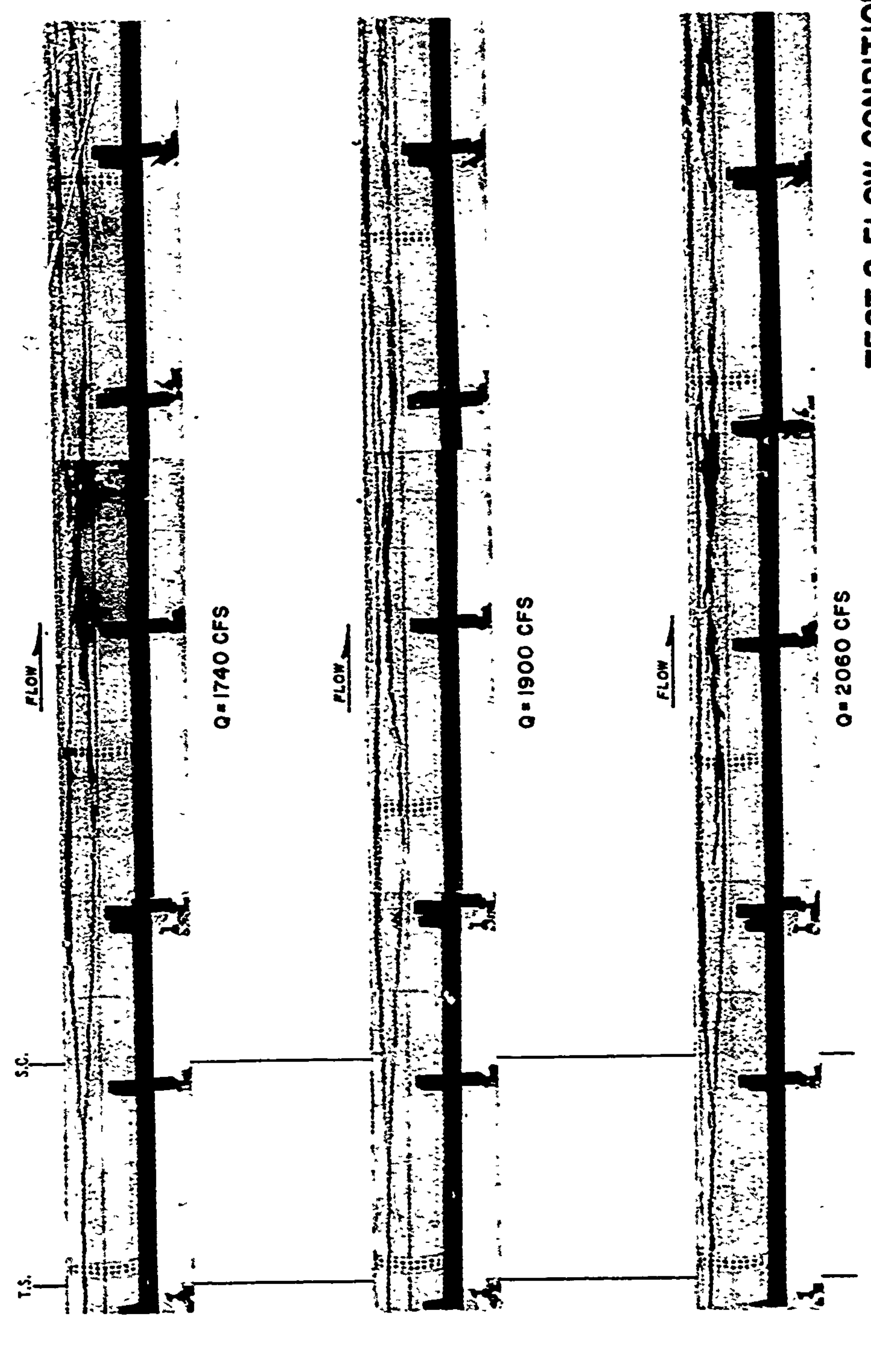


NOTE: UPSTREAM DEPTH CONTROL AT T.S.

LEGEND
1740 CFS
1900 CFS
2060 CFS

WATER–SURFACE PROFILES
TEST 2

PLATE A9



TEST 2 FLOW CONDITIONS
IN CONDUIT WITH SIMPLE CURVE
AND SPIRAL TRANSITIONS

PLATE A10

APPENDIX B: SUPERCRITICAL FLOW IN VERDUGO WASH CHANNEL

INTRODUCTION

1. In the design of curved channels, one of the more important hydraulic problems is the determination of the water-surface profile. The superelevation in the curve must be determined sc that sufficient wall heights may be provided. This appendix gives a summary of the hydraulic results obtained from the model tests for the final design of the Verdugo Wash channel and presents a comparison of the computed superelevation with those obtained from the model tests.

2. In connection with the improvement of the Verdugo Wash channel, the Los Angeles District Hydraulic Laboratory constructed an undistorted 1:30-scale model of the channel from the debris basin, sta 301+21.22 downstream to sta 256+29.46. This is shown in photograph B1. The channel is trapezoidal in cross section with a base width of 25 ft and side slopes of 1 vertical on 2 horizontal. Three curves exist in this reach, two of which have spiral transition curves on each end.

TEST

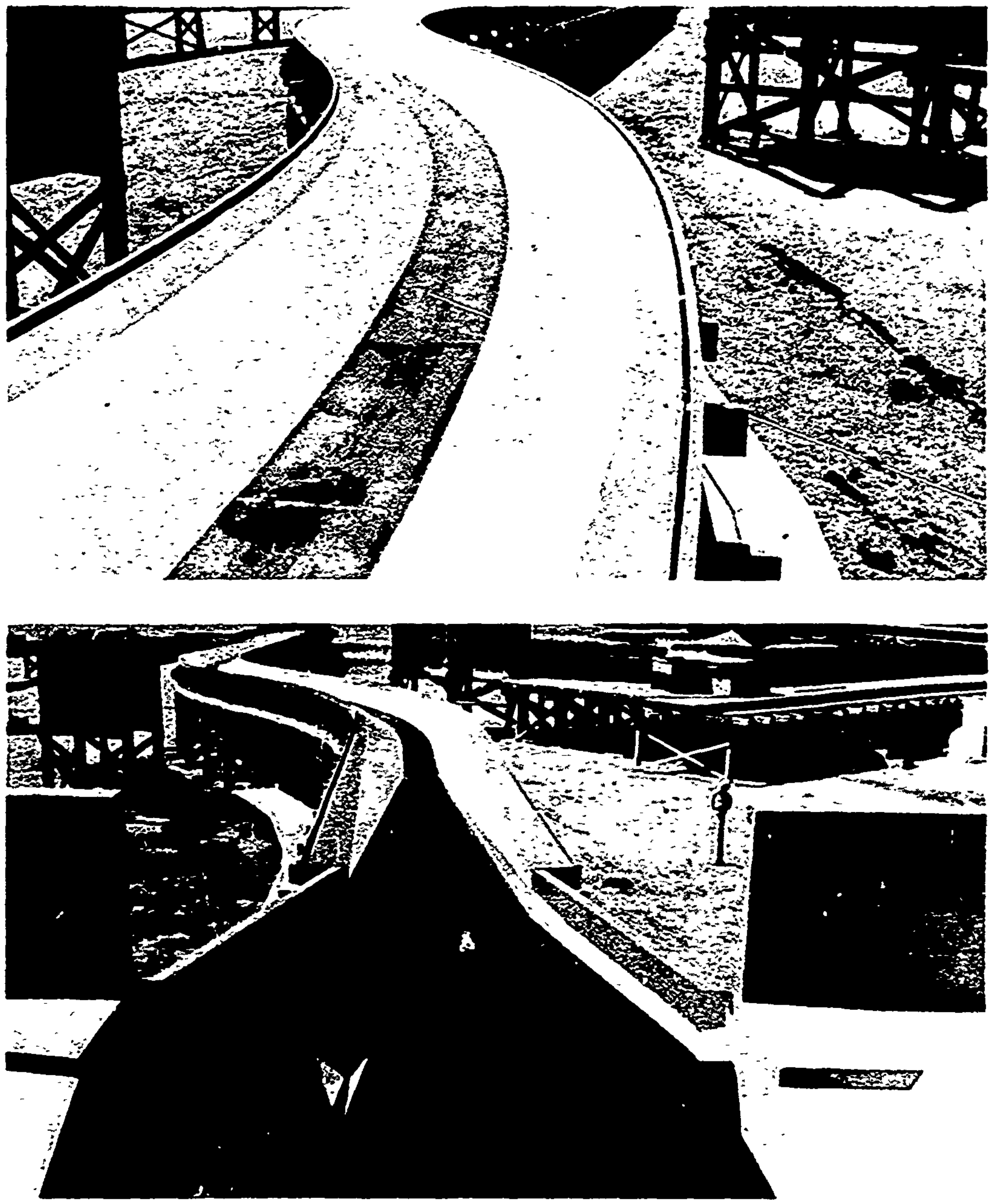
3. The model, as constructed for the final design, was tested for the design discharge of 18,000 cfs. The data taken for this test consisted of water-surface elevations and velocity distribution measurements. Design wall heights were determined from the water-surface profiles measured in the model. The amount of additional wall heights to be allowed was one of the problems to be resolved. In locations where maximum superelevation occurs, the wall heights must be increased over and above the usual freeboard provided for channels with stable flow. However, the spiral transition curves effectively stabilized the superelevated flow between the circular curve and the tangent downstream for both curves. No disturbance developed in the channel and the freeboard provided in this design was adequate (photograph B2). Model water-surface profiles along the right and left walls are shown in plates B1 and B2. Velocity distribution cross sections

are shown in plates B3 and B4. Details of the observed superelevations of water surface along the right and left walls relative to normal depth are shown in plate B5. These measurements afford an opportunity to compare model data with theoretical results (plate B5). Superelevations of the water surface were computed by the formula $\frac{V^2T}{gR}$ and are listed in the tabulation below. The superelevation is considered as the rise above normal depth. The computed superelevation of the water surface ranged from 1.0 to 4.2 ft.

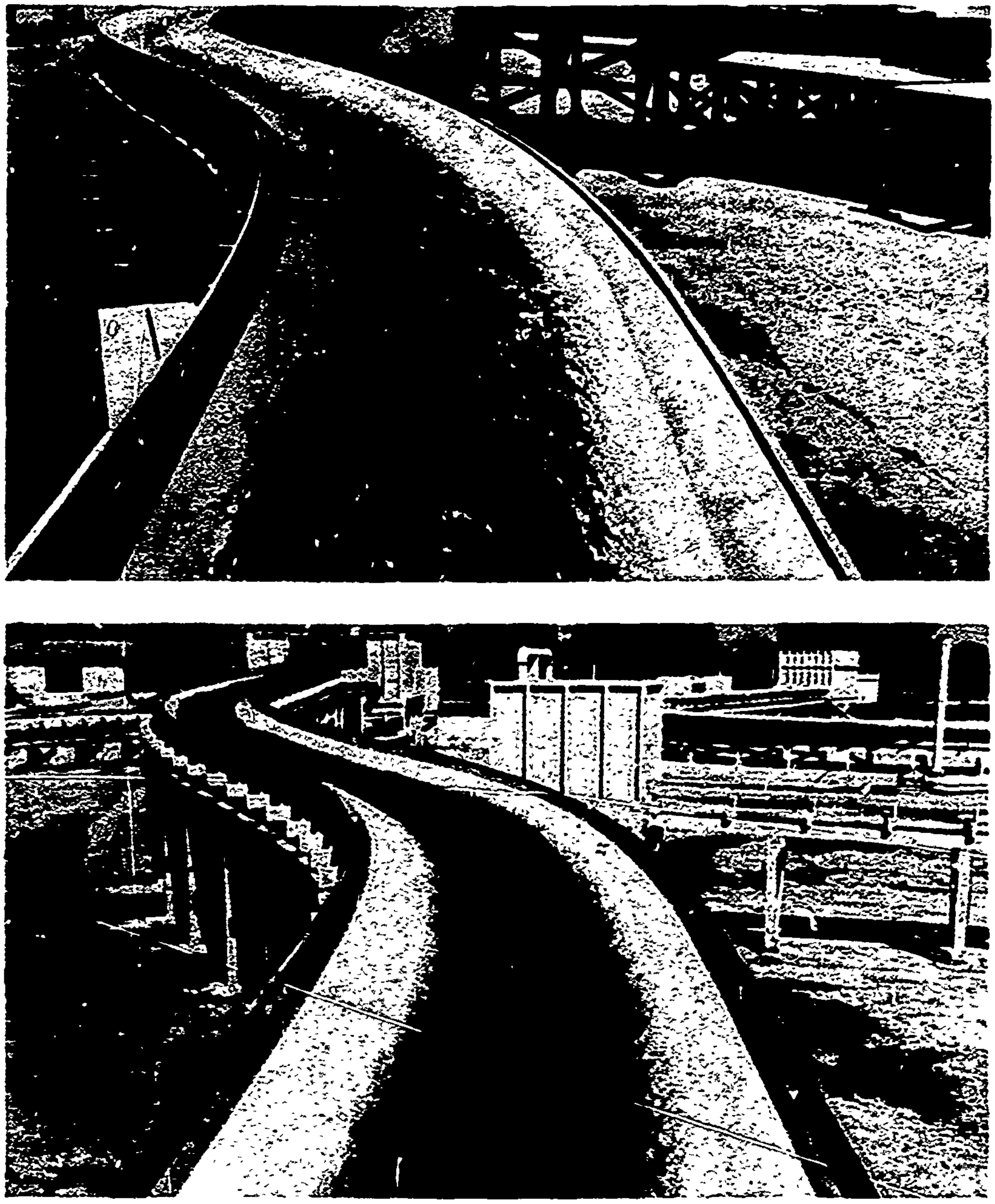
Section	Station	V fps	T ft	R ft	$\frac{V^2T}{gR}$ ft
Trapezoidal section	S.T. 293+60.44	--	--	--	--
	C.S. 291+10.44	47.6	60.5	1800	2.4
	S.C. 286+19.28	47.6	60.5	1800	2.4
	T.S. 283+69.28	--	--	--	--
	S.T. 283+62.71	--	--	--	--
	C.S. 281+12.71	51.7	58.4	1150	4.2
	S.C. 278+57.30	51.7	58.4	1150	4.2
	T.S. 276+07.30	--	--	--	--
Composite section transition	E.C. 259+79.37	--	--	--	--
	258+91.87	54.0	68.5	6385.44	1.0
	257+16.94	55.6	51.5	6385.44	0.8
Rectangle	B.C. 256+29.46	55.6	43.0	6385.44	0.7

CONCLUSIONS

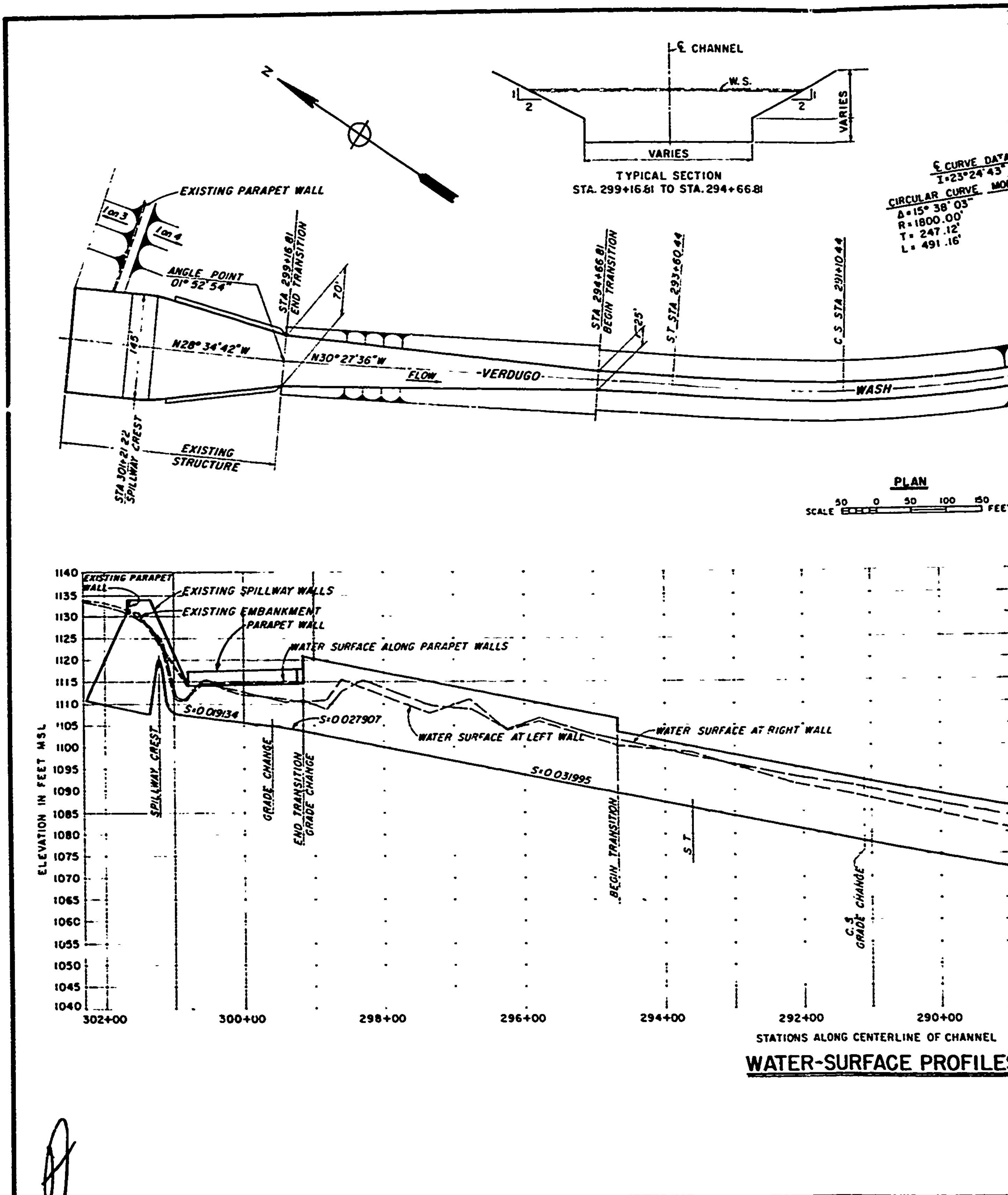
4. The differences between the computed and observed superelevations in the channel curves are attributed to waves in the converging channel section upstream of the curves (plate B1) that attenuate downstream into the curves. These waves are believed to effect oscillations in the flow at the beginning of the curves that result in abnormal superelevation conditions. This type of disturbance can also occur when tangent distances between curves are very short. Some of the disturbance possibly can be attributed to the channel cross-section geometry which combines rectangular and trapezoidal features.



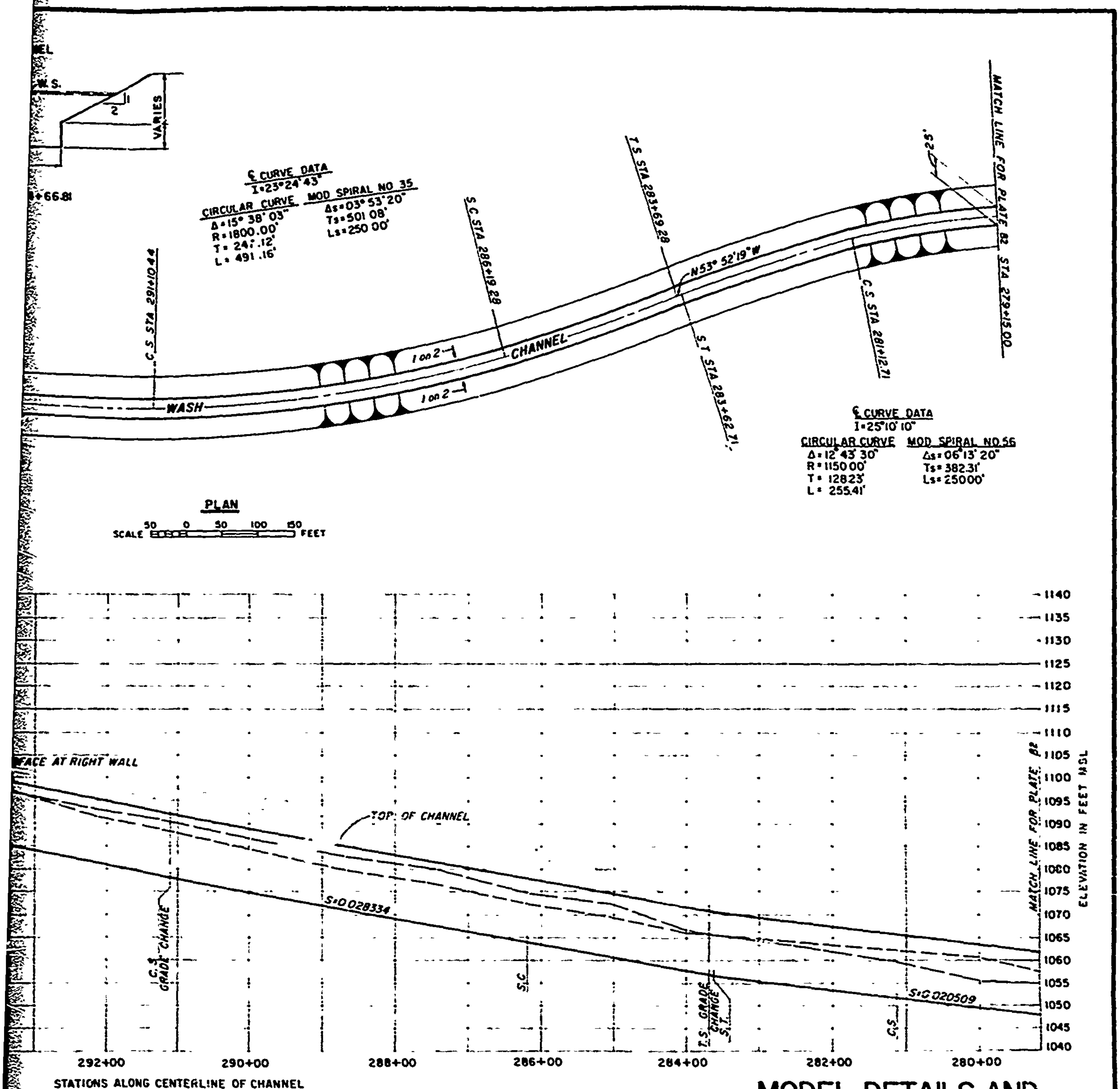
Photograph B1. Downstream views of 1:30-scale model of Verdugo Wash channel



Photograph B2. Flow conditions with design discharge of 18,000 cfs



WATER-SURFACE PROFILES



WATER-SURFACE PROFILES

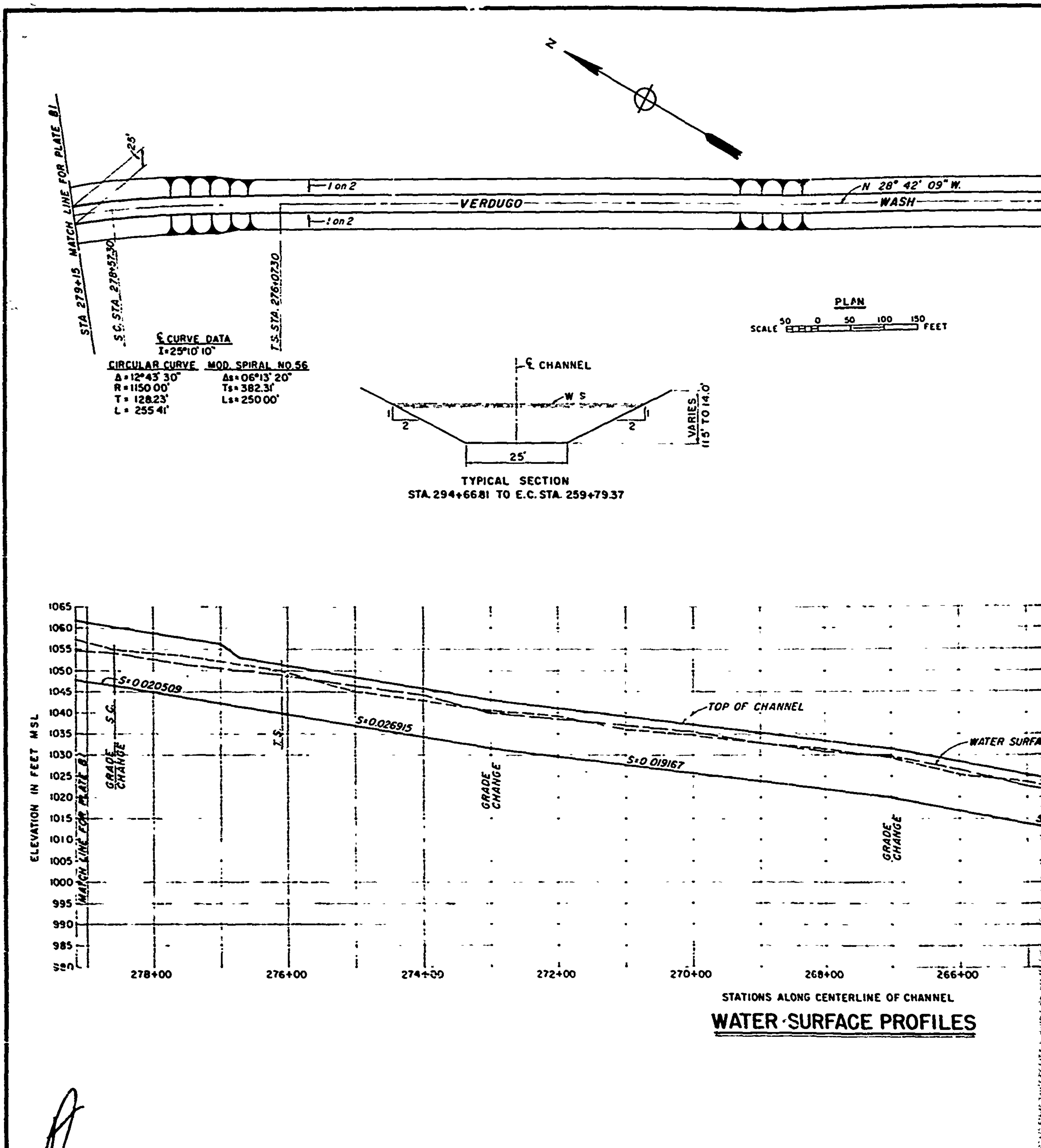
MODEL DETAILS AND WATER-SURFACE PROFILES

FINAL DESIGN

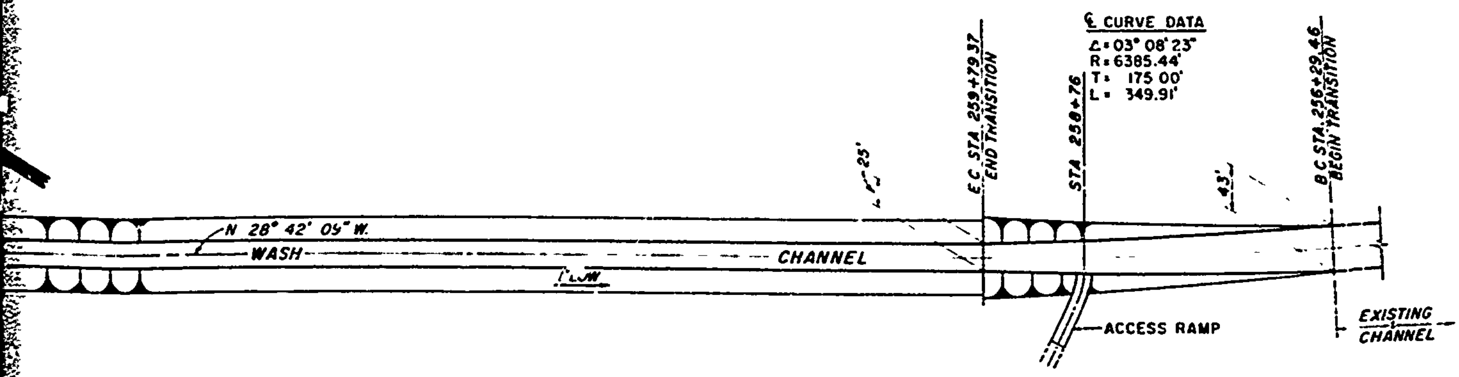
DISCHARGE 18,000 CFS

STA 302+00—280+00

PLATE 81

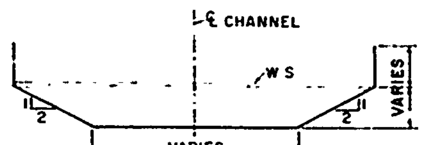


WATER-SURFACE PROFILES

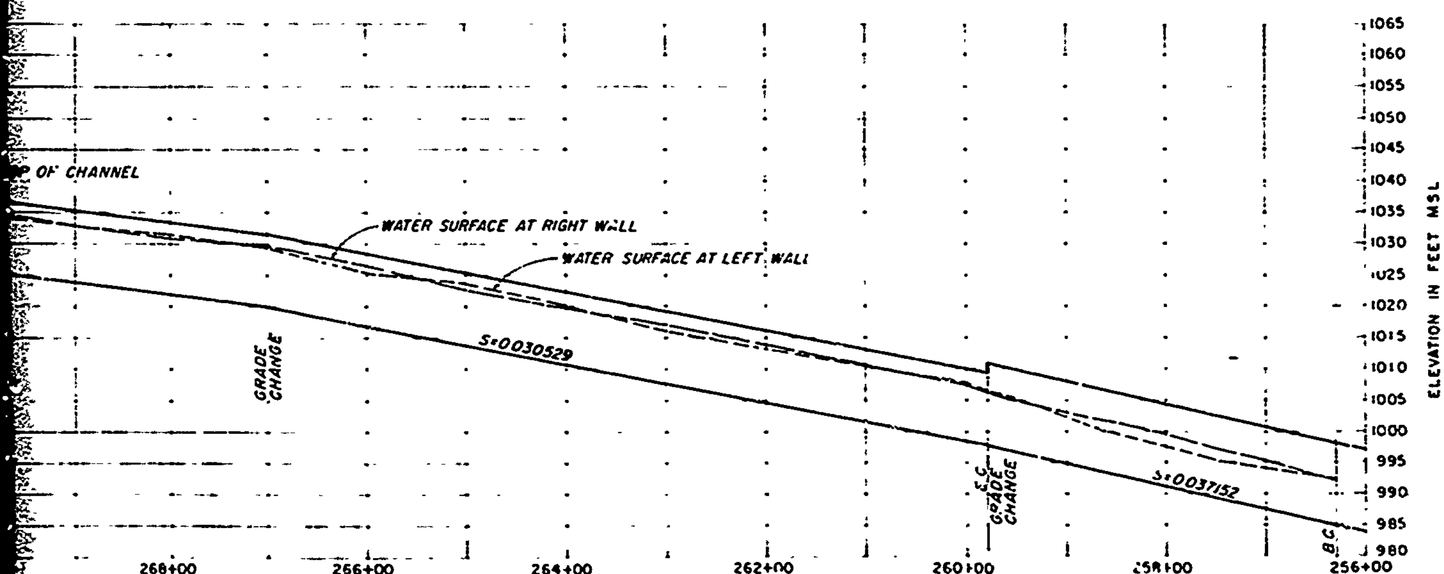


PLAN

SCALE 50 0 50 100 150 FEET



TYPICAL SECTION
E. C. STA. 259+79.37 TO B C. STA. 256+29.46

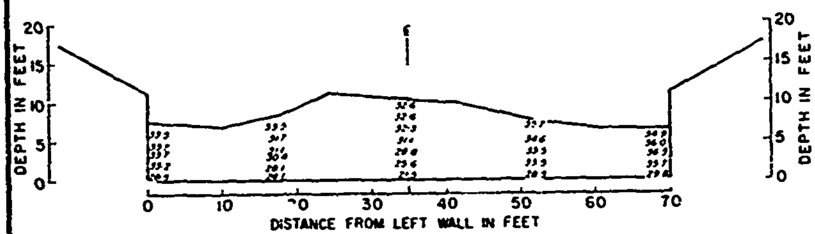


STATIONS ALONG CENTERLINE OF CHANNEL

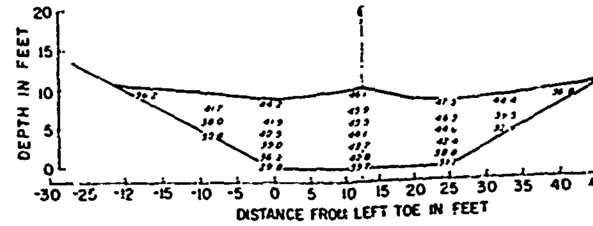
WATER-SURFACE PROFILES

MODEL DETAILS AND WATER-SURFACE PROFILES
FINAL DESIGN
DISCHARGE 18,000 CFS
STA 278+00–256+00

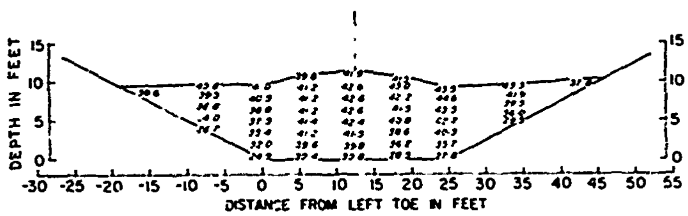
PLATE B2



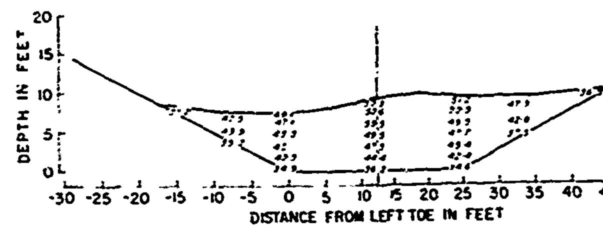
E. T. STA. 299+16.81



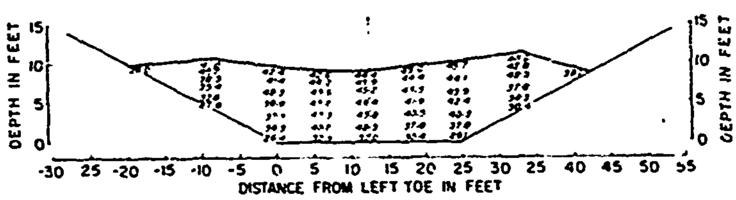
S. T. STA. 293+60.44



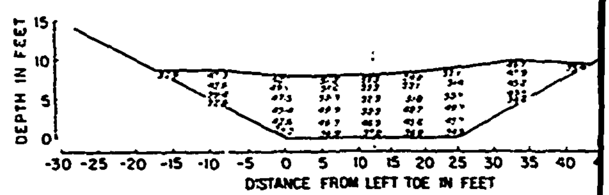
B. T. STA. 294+66.81



C.S. STA. 291+10.44

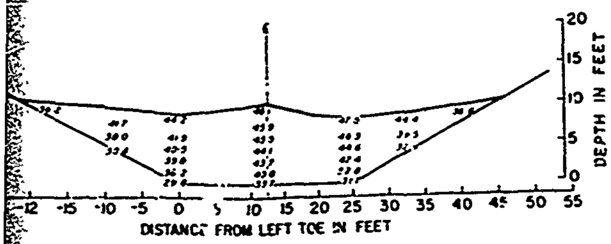


STA. 294+00

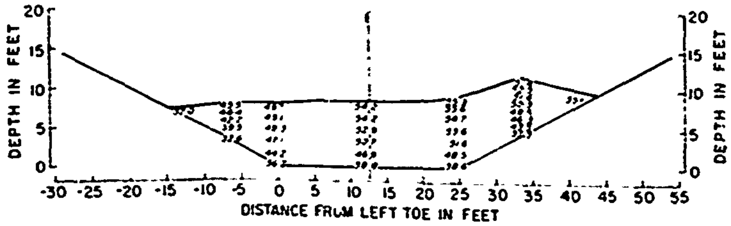


STA. 289+50

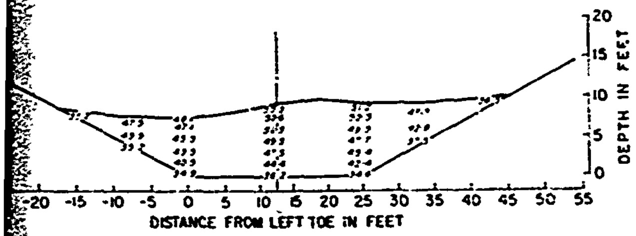
NOTE.
ALL SECTIONS SHOWN LOOKING DOWNSTREAM.
VELOCITIES ARE IN FEET PER SECOND.



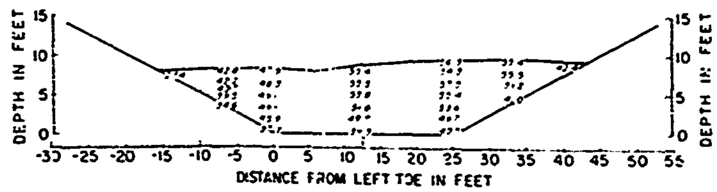
S.T. STA. 293+60.44



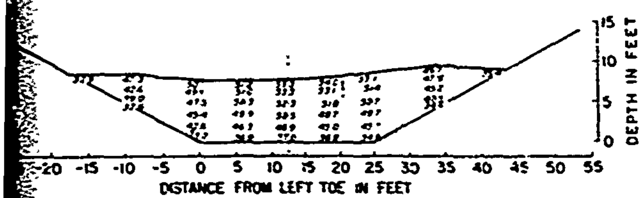
STA. 288+00



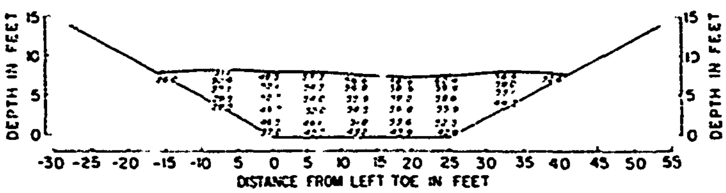
C.S. STA. 291+10.44



S.C. STA. 286+19.28



STA. 283+50



T.S. STA. 283+69.28

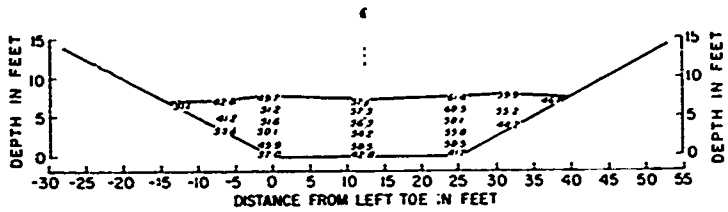
VELOCITY DISTRIBUTION

FINAL DESIGN

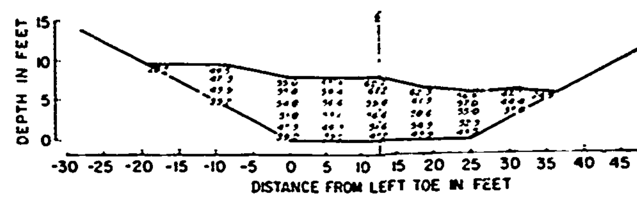
DISCHARGE 18,000 CFS

STA 299+16.81–283+69.28

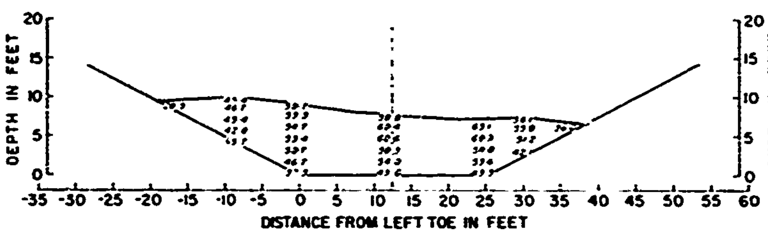
PLATE B3



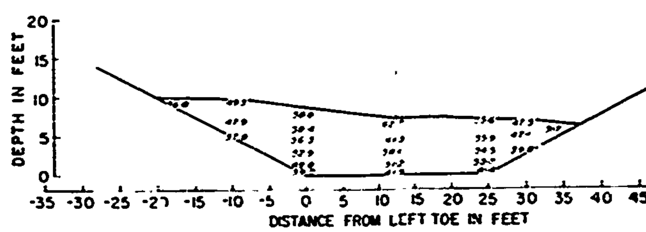
S.T. STA. 283+62.71



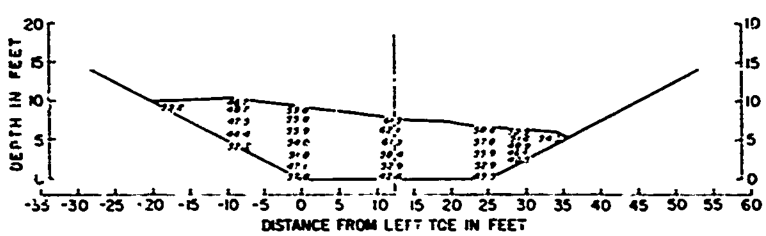
STA. 279+50



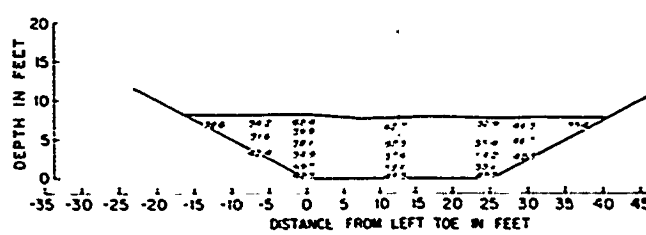
C.S. STA. 281+12.71



S.C STA. 278+57.30

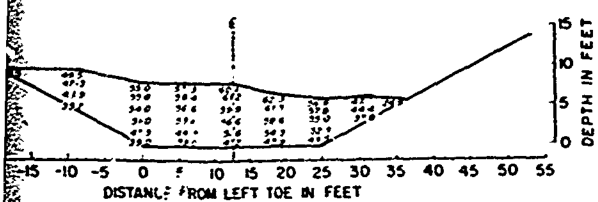


STA. 280+00

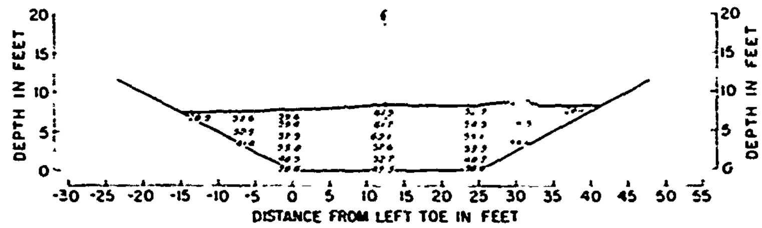


T.S STA 276+07.30

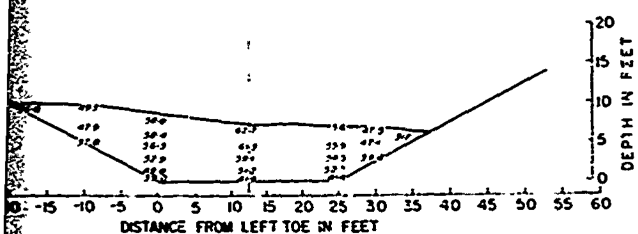
NOTE
ALL SECTIONS SHOWN LOOKING DOWNSTREAM.
VELOCITIES ARE IN FEET PER SECOND.



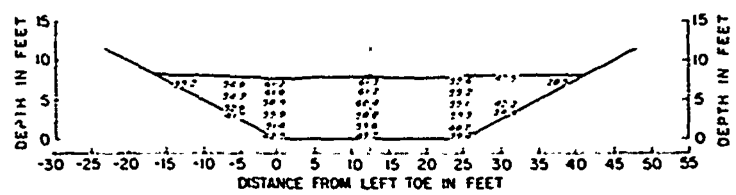
STA. 279+50



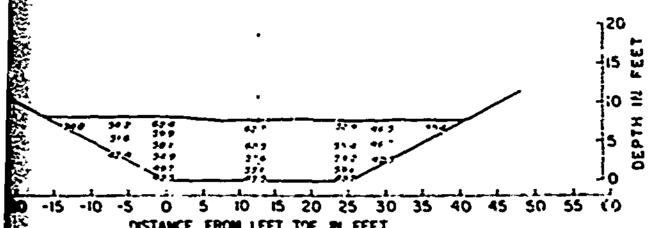
STA 275+00



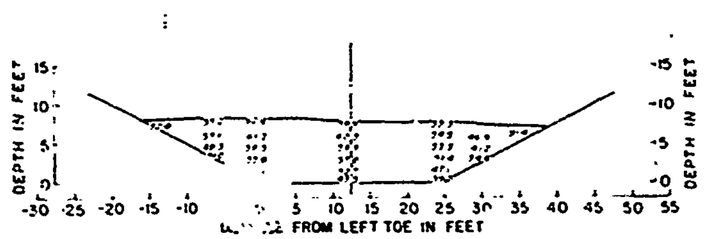
S.C. STA. 278+57.30



STA. 274+00



T.S STA. 276+07.30



STA 273+00

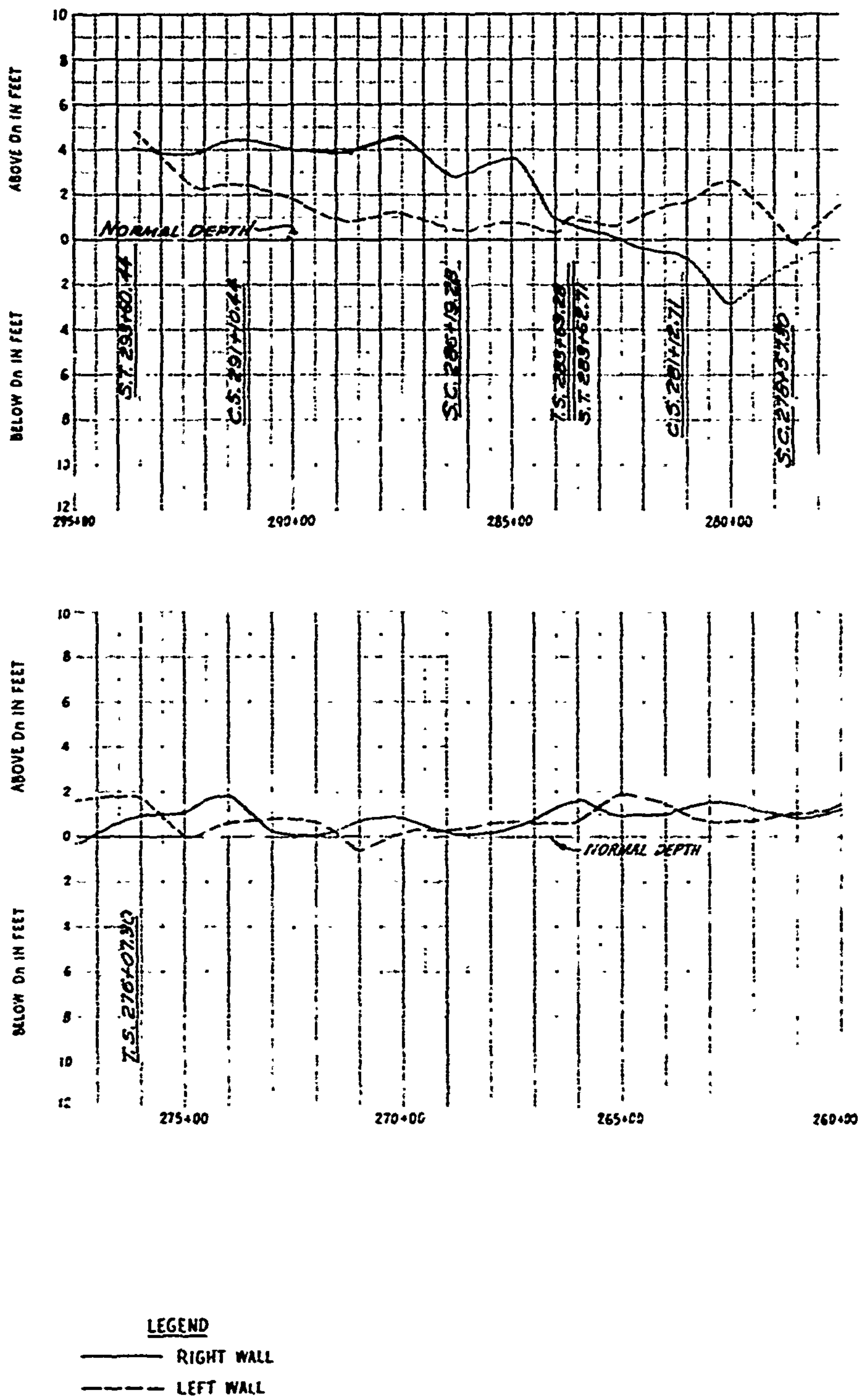
VELOCITY DISTRIBUTION

FINAL DESIGN

DISCHARGE 18,000 CFS

STA 283+62.71 – 273+00

PLATE B4



WATER-SURFACE PROFILES
VERDUGO WASH CHANNEL
DISCHARGE 18,000 CFS

PLATE B5